Dipl.-Ing. Matthias Wolf, BSc

Counteracting demographic challenges in industrial blue-collar work

Development of a structured approach for the identification of age-critical workplaces and their adaption by physical assistance

DOCTORAL THESIS

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Supervisors

Univ.-Prof. Dr.techn. Christian Ramsauer

Institute of Innovation and Industrial Management

Prof. Dr.-Ing. Ralph Bruder

Institute for Ergonomics and Human Factors, Technische Universität Darmstadt

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Affidavit

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Abstract

The demographic changes in OECD countries lead to an on average older population. Accordingly, the effective retirement age is raised in affected countries. In connection with this development, the average working life will also be extended. Companies therefore face the challenge of providing age-appropriate working conditions for their employees.

Scientific studies have shown employees in the older age category have higher work absenteeism rates and have lower productivity, mainly due to musculoskeletal disorders, especially in physical demanding work. These problems often result from physical overstrain in the workplace, caused by different developments in work demands and worker resources. While the physical workloads at the workplace remain constant, the physical performance prerequisites decrease with increasing age. One reason for physical overstrain is that work requirements are not adapted to age. Therefore, the group of older employees in physically demanding occupations is of particular relevance in this context.

Studies conducted in this area focus on the automotive industry and on traditional solutions to reduce stress through mechanisation, automation and changes in the work organisation. In this context, the perceived strain, which is particularly relevant in connection with changing skills, has usually been neglected. In connection with the progressive technical development of physical assistance systems, new possibilities arise to improve this component.

The aim of this thesis is to develop a process model that allows the identification of age-critical work stress and its reduction by physical assistance systems, while specifically taking into account the strain component. Based on a field study in heavy machinery manufacturing and the retail sector, such a process model is developed and validated in a prototypical application. From the synthesis of the results of empirical investigations, industry-relevant requirements for the age-differentiated assessment of workplaces were derived. In a first step, a methodology and tool for ergonomic workplace assessment was developed, which takes into account average ability changes while ageing and enables an age-differentiated ergonomic evaluation. Subsequently, a classification logic and assessment methodology for industry-relevant assistance systems for stress and strain reduction was developed, which supports a systematic ergonomic improvement process. Finally, a method for the structured implementation and testing of different assistance systems in industry was developed, which takes into account not only the objective stress reduction but also the subjective strain of the employees.

The presented results complement the existing literature with age-specific stress factors and a methodology for age-differentiated assessment of physical work activities as well as with a methodology for the identification and implementation of appropriate physical assistance systems to reduce strain.

The developed procedure provides practitioners with a methodology and industry tailored user-friendly tools that support the preventive design of age-appropriate working conditions and thus counteract the demographic challenges in industry.

Kurzfassung

Die demographischen Veränderungen in OECD Ländern führt zu einer durchschnittlich älteren Bevölkerung. Mit der verbundenen Anhebung des faktischen Pensionsantrittsalters in betroffenen Ländern verlängert sich das durchschnittliche Erwerbsleben. Unternehmen stehen daher vor der Herausforderung altersadäquate Arbeitsbedingungen bereitzustellen.

Wissenschaftliche Studien belegen, dass die Gruppe der älteren MitarbeiterInnen vermehrt höhere Fehlzeiten und verminderte Produktivität, vor allem aufgrund von Beschwerden im Muskelskelettapparat, aufweisen. Diese Probleme resultieren häufig aus körperlicher Überbeanspruchung am Arbeitsplatz, die durch unterschiedlicher Entwicklungen von Arbeitsanforderungen und Beschäftigtenressourcen ausgelöst werden Während die physischen Arbeitsbelastungen am Arbeitsplatz konstant bleiben, nehmen die physischen Leistungsvoraussetzungen mit zunehmendem Alter ab. Ein Grund für physische Überbeanspruchungen sind nicht an das Alter angepasste Arbeitsanforderungen, weshalb die Gruppe der älteren MitarbeiterInnen in physisch belastenden Berufsgruppen in diesem Zusammenhang von besonderer Relevanz ist. Studien in diesem Bereich fokussieren vor allem auf die Automobilindustrie, und auf traditionelle Lösungen zur Verminderung der Belastung durch Mechanisierung, Automatisierung, und Veränderung der Arbeitsorganisation. Dabei wurde die, im Zusammenhang mit sich verändernden Fähigkeiten besonders relevante, Beanspruchung von MitarbeiterInnen meist vernachlässigt. Im Zusammenhang mit der fortschreitenden technischen Entwicklung physischer Assistenzsysteme ergeben sich neue Möglichkeiten gezielt diese Beanspruchungskomponente zu verbessern.

Ziel der Arbeit ist die Entwicklung eines Prozessmodells, dass unter Berücksichtigung der Beanspruchungskomponente eine Identifikation von alterskritischen Belastungen und deren Reduktion durch physische Assistenzsysteme ermöglicht. Dazu wurde im Rahmen dieser Arbeit, basierend auf einer Feldstudie im Großmaschinenbau und Handel, solch ein Prozessmodell entwickelt und in einer prototypischen Anwendung validiert. Aus der Synthese der Ergebnisse von empirischen Untersuchungen werden industrierelevante Anforderungen an die altersdifferenzierte Bewertung von Arbeitsplätzen abgeleitet. Dazu wurde eine Methode zur ergonomischen Arbeitsplatzbewertung entwickelt, welche durchschnittliche Fähigkeitsverläufe im Alter berücksichtigt und eine altersdifferenzierte ergonomische Bewertung ermöglicht. Anschließend wurde eine Klassifizierungslogik und Bewertungsmethodik für industrierelevante Assistenzsysteme zur Belastungs- und Beanspruchungsreduktion erstellt, die in weiterer Folge einen systematischen ergonomischen Verbesserungsprozess unterstützt. Zum Abschluss wurde ein Verfahren zur strukturierten Implementierung und Testung verschiedener Assistenzsysteme entwickelt, welches neben der objektiven Belastungsreduktion auch die subjektive Beanspruchung der MitarbeiterInnen berücksichtigt.

Die vorgestellten Ergebnisse ergänzen die vorhandene Literatur mit altersspezifischen Belastungsfaktoren und einer Methodik zur altersdifferenzierten Bewertung physischer Arbeitstätigkeiten und zur Identifikation und Implementierung passender physischen Assistenzsystemen. Durch das entwickelte Vorgehen erhalten PraktikerInnen eine Methodik mit anwenderfreundlichen Werkzeugen, die bei einer präventiven Gestaltung von altersadäquaten Arbeitsbedingungen unterstützt und somit den demographischen Herausforderungen in der Industrie entgegenwirkt.

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Contents

Figures

Tables

1 INTRODUCTION

This chapter introduces the current situation in the industry, forecasted demographic developments for population ageing and related impacts on employment. Consequently, demographic challenges are derived and possible solutions are outlined. Based on this introduction the objectives of this thesis and the research guiding question are formulated. In addition, the background of the conducted research is outlined and the structure of the thesis is described.

1.1 INITIAL SITUATION

The manufacturing industry remains a central driver for economic growth, societal wealth and improved standard of living in central Europe. In the past technology, particularly automation, has been a major driver for increasing manufacturing's productivity (Mital and Pennathur, 2004, p. 295). Further, process optimization and rationalization with a focus on lean production systems and the avoidance of waste [see (Ohno, 2006)] have been introduced in many production systems, to enhance process efficiency (Frieling *et al.*, 2013, p. 203; Neuhaus, 2010, p. 80). The implementation of efficiency optimized processes, as well as the use of innovative manufacturing technologies, require new tasks to be performed and thereby lead to new requirements for the people employed in the system (Keil and Spanner-Ulmer, 2012, p. 178). Instead of just focusing on technological and process improvements, it has become significantly more important to focus on the workers as central part of the production system as means to increase the overall productivity to remain competitive in globalized and changing markets (Jäger *et al.*, 2000; Botthof and Hartmann, 2015, pp. 4–6).

The introduction of automation technology and lean principles in work systems usually results in reduced process cycle times as well as the revealing and elimination of non-value adding activities (Frieling *et al.*, 2013, pp. 220–224). This reduction of cycle times, the avoidance of hidden breaks and the elimination of non-value adding activities at the one hand increase the process and production efficiency, but on the other hand also results in an aggregation of work contents, as well as an intensification of the workload, an increase of work stress, and higher work strain experienced by the workers point of view (Frieling *et al.*, 2013, p. 224).

Despite the ongoing trend in automation and mechanization in industry, many workers are still exposed to physical workload due to material handling (about 32% of the working population in the EU), repetitive movements (60%) and awkward body postures (43%) as stated in recent reports of European working conditions (Eurofound and International Labour Organization, 2019, p. 17). The existing work content aggregation, that leads to one-sided workloads and the avoidance of hidden breaks, also causes a higher risk for physical overloading (Kotzab *et al.*, 2011, pp. 81–86; Schlick *et al.*, 2013, p. 210). The implementation of such production structures creates numerous risks, especially in assembly and logistics work of different industries. These risks include in particular: manual load handling, such as lifting and carrying pieces exceeding 10 kg, forced body postures, work tasks with increased energy or strength usage, utilization of hands and arms as a tool (knocking, hammering, turning, e.g. during clipping) and repetitive tasks with high manual operation frequencies (Frieling *et al.*, 2013, p. 203). This working conditions can lead to problems especially for older employees, but also deserve critical attention from younger workers (Schlick et al. 2013, p. 203).

1.1.1 The demographic change and its impact on employment

Due to a complex combination of social and technological improvements including better prosperity, wealthy diet, better medical and social care, and improved work conditions the anticipated average life increases (WHO, 2016, pp. 10–17; Riley, 2004, pp. 786–788). This development is flanked by a birth rate below the replacement fertility level and the ageing of the baby boomer generation (Morschhäuser, 2002, p. 10; Statistik Austria, 2019b). Therefore, the median age of the European population, as well as the population of most OECD countries, is steadily increasing from an average age of 29 years in 1950 to 47 years in 2040 (UNDP, 2019). The the trend in population ageing for selected nations is shown in Figure 1. For Austria an increase of the median age of population form 42 years in 2010 to 48 in 2040 is forecasted. Only Japan, with an age median of 54 years, will have an older population, while the age median of the USA is projected to be six years lower in 2040 at 42 years.

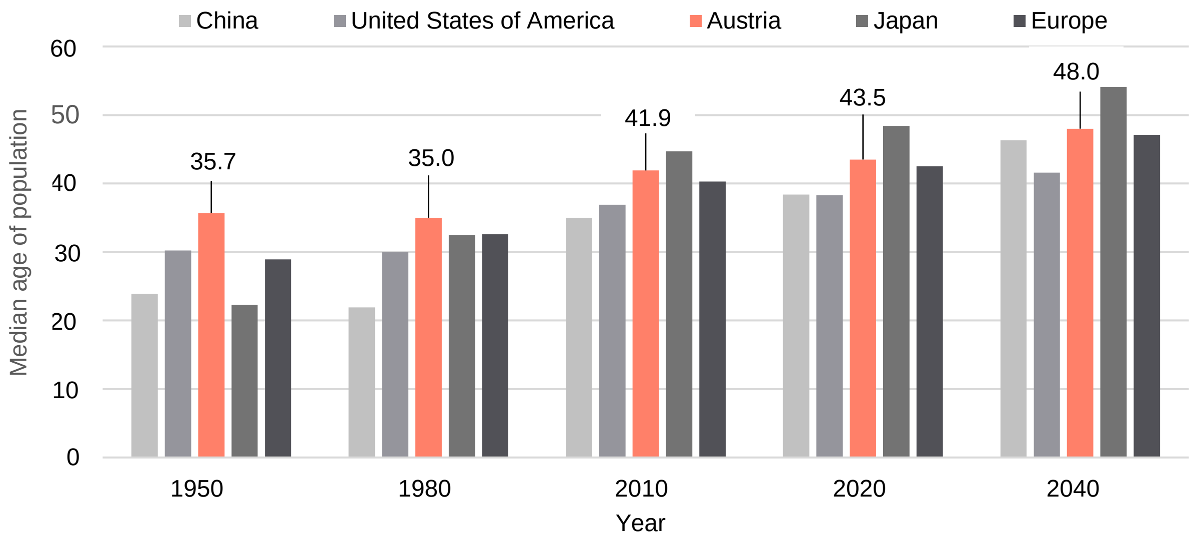

Figure 1: Average age of populations of different countries (own illustration based on data from (UNDP, 2019)

The demographic change also leads to a situation where the availability of workers for different industries and occupations is declining. According to forecast models, only 60% of Austria's population will be of working age (between 15 and 65 years) in 2039, compared to 67% in 2018. This results in a total loss of workforce capacity of roughly 280.000 people (Statistik Austria, 2019b). Figure 2 illustrates the demographic forecast for Austria from the year 2018 to 2040. It shows a decline of the working age population by 7%, whereas the amount of people aged 65 years and older is increasing by the same amount.

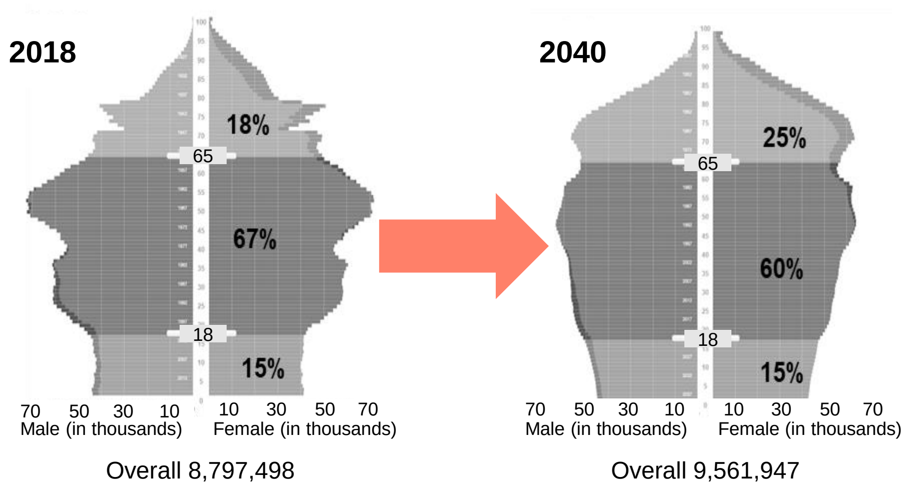

Figure 2: Demographic change in Austria according to the federal statistic office (Statistik Austria, 2019)

Thus, the demographic change, with its structural changes in age and composition of the population in Europe has an impact on the working population. While the number of employees aged 50 years and younger decreases, the proportion of older employees is increasing (Eurostat, 2019). Further, an increase in age of retirement entry is discussed in several countries, resulting in an increasing number of older individuals remaining in the workforce (Varianou-Mikellidou *et al.*, 2019, p. 231).

An intra-European comparison shows that, despite these figures, most European countries, including Austria, have not yet responded sufficiently to demographic developments. While the employment rate of the younger age groups remains at high levels (80% on average), the employment rate of persons aged 55 years and older at roughly 55% in the European Union is, by far, lower (Vermeulen, 2017). For example, in Austria employment rates for workers under 55 years are around 88%, while the rate for people aged 55 years till legal retirement is only around 54% (Statistik Austria, 2019b, p. 42). Therefore, in a time of increasing skill shortage in many industries (Bokranz & Landau 2012, p 250), it has become paramount to prolong the working life and to keep elderly and often experienced workforce in employment, assuring they have a high workability as stated in the EU's Lisbon Strategy16 (EUOSH, 2009, p. 29).

As a result of different supportive measures the employment rate of employees aged 60-64 years already roughly doubled in recent years and currently is at approximately 59% in the European Union (Eurostat, 2019). This indicates a higher share of elderly workers in most companies, which might have special abilities, skills and needs concerning their work task, operating means, and work environment. Thus, most companies are faced with the challenge of securing the long term productivity and competitiveness with aging employees and at the same time protecting their employee's health (Jaeger, 2015a).

1.1.2 Demographic challenges and economic implications

Employees of all ages are exposed to a large number of different work stresses. In industrial work systems these stresses can be caused by the work tasks, the working environment, the work organisation and by human-machine-interaction (Schlick, Bruder & Luczak, 2010). Especially in companies where a high proportion of manual physical work is carried out under restrictive conditions, the increasing health risks and stresses have to be compensated by offering well designed work places. The steadily increasing performance requirements, in combination with the continuing increase in average employees age presents the challenge of ensuring that employees are deployed in a way that is appropriate to their abilities. New planning and design instruments for skill- and age-differentiated personnel deployment and work design are needed, especially for the increasing number of employees with ability limitations and deployment restrictions. Therefore, also reintegration and age-management methods are currently missing. (Scheller *et al.*, 2015, p. 137) Without such management systems and measures companies risk economic losses. The benefits that can derive from applying such measures were shown by an international study that determined the potential return on investment in prevention within companies. Based on a scientific approach, this study revealed that for every Euro an employer invests in preventive measures in the workplace, a return of up to 2.2 Euro can be generated. Prevention thus has an exceptionally high return on investment of 1/2.2 € (Zana *et al.*, 2019, p. 408).

The higher proportion of older employees in the working population and the increase in their employment rate (Statistik Austria, 2019, 2019b), make an examination of age and the associated occupational effects unavoidable. Even if ageing is a highly individual process and the related general decline of physical abilities is partially reversible, as a general trend, dexterity, responsiveness, perception and strength decrease from the mid-twenties, while experience and competence grow. The development and reduction of abilities are subject to genetic conditions, environmental influences, personal health status and training (Schlick *et al.*, 2010, pp. 116–134). Thus, it is not possible to conclude from the calendric individual age to restrictions in employee skills, the workability or work performance. Whether and how exactly age-related performance changes occur must be examined separately for each type of work (Zülch and Becker, 2006). The work-related changes in performance can only be compensated to a certain extent (Ilmarinen, 2001; Kenny *et al.*, 2008), partly by physical training (Gall and Parkhouse, 2004, p. 648), partly by behavioural changes and operational experience (Börsch-Supan *et al.*, 2007), and are offset by the constant requirements of the work system (Ilmarinen and Rutenfranz, 1980; Ilmarinen, 2002a, p. 9). This discrepancy can lead to an overload of older employees, which, in turn can manifest itself in an accumulation of stress effects and related consequences over the course of the working life (Buck, 2002a; Jaeger, 2015a).

It has been determined that, with increasing age, the probability of the occurrence of such restrictions or changes in performance statistically increases. Older employees fall ill and have accidents less often, but more severely than younger people (Leoni, 2019, p. 21; Leoni and Böheim, 2018, p. 21; Silverstein, 2008). As illustrated in Figure 3 for all occupations in Austria older workers have on average more days of incapacity at work due to this occupational consequences induced by ageing.

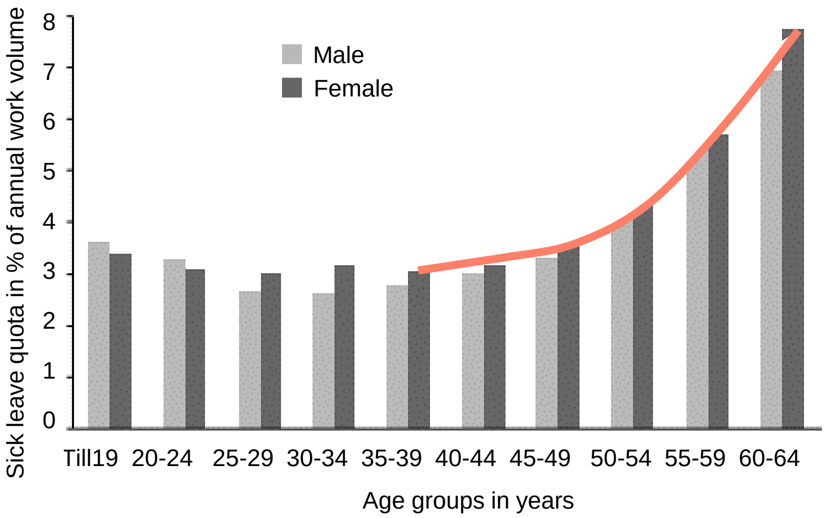

Figure 3: Sick days as a percentage of the yearly work volume over workers age (Leoni, 2019, p. 23)

A clear trend in the increase in annual sick leave days is identifiable. While sick days remain constant at roughly 3% of the yearly work volume over the age groups from 19 to 45 years this percentage more than doubles between the ages of 45 and 65 to about 7% indicating increasing problems for the elderly worker groups.

A major cause for these problems, as well as of absenteeism and early retirement, are musculoskeletal health problems (EUOSH, 2007). The collective term of musculoskeletal disorders (MSD) encompasses a large number of disorders, symptoms and illnesses. Musculoskeletal disorders are a leading cause of disability worldwide and make up a significant proportion of all recognized occupational diseases (Theo *et al.*, 2017, p. 1245). A study conducted in 2016 in several European countries resulted in high shares of MSD compared to all other recognized occupational diseases. This study resulted in MSD rates of 70-80% of all registered occupational diseases in France, Belgium and Italy while Germany, Austria, Denmark, Finland and Switzerland rates are around 20% (Zana et al 2019, p.405). In the European Union, annually about 43% of the workforce suffers from low back, neck and shoulder pain (Eurofound and International Labour Organization 2019, p 64) caused by MSD. In Austria, 21.4% of sick leaves are caused by MSD. Therefore, MSD are the most common cause of illness followed by psychological (16.7%) and the diseases of the respiratory system (Leoni and Böheim, 2018, p. 46) as shown in Figure 4.

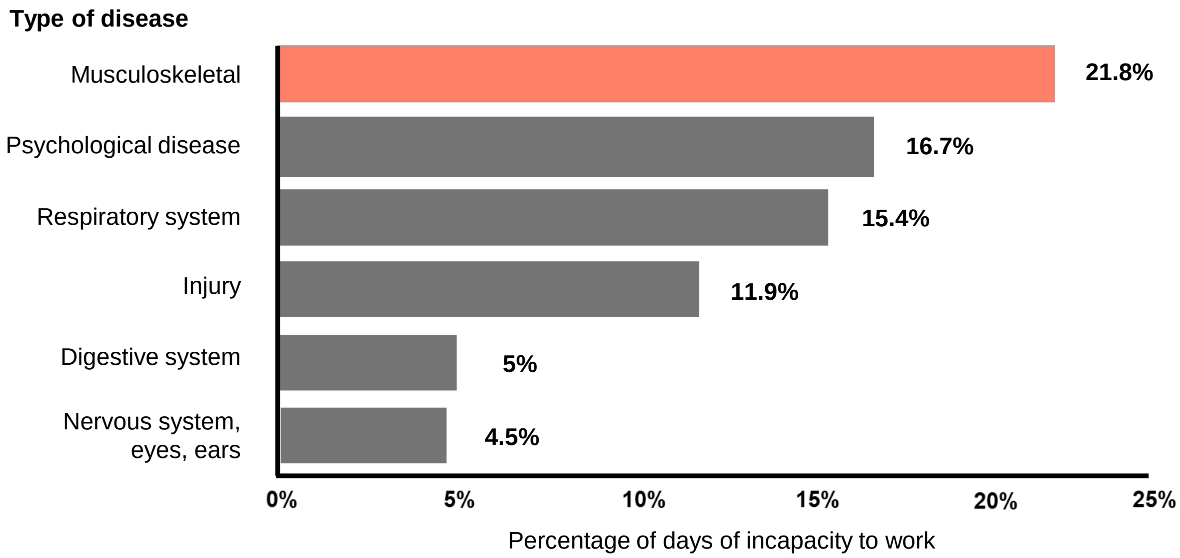

Figure 4: Causes of sick leave as percentage of yearly work capacity in Austria (Leoni and Böheim, 2018, p. 46)

In the production sector, more than 35% of days of incapacity to work are devoted to the musculoskeletal system (Prasch 2010, p. 61). This leads to high direct and indirect costs for the employer and society as discussed by several authors.[1] In terms of the economic impact on company level, Baase (2007) evaluated the relationship between chronic illnesses and labour productivity. The results of this study showed that the total costs of chronic illnesses in an examined company amounted for 10.7% of the personnel costs and the share of costs due to limited working capacity was 6.8% of total personnel costs (Baase 2007 cited in Egbers, 2013, p. 12).

This shows that every year countries and companies in the European Union spend millions of Euros on musculoskeletal sick leaves, constantly ranked as number one work disease. This considerable impact on countries as a whole can be seen in Figure 5 in the example of Germany. In relation to the Austrian economy a study estimated the total costs of illness-related absences at work to amount for 2.1% to 3.1% of the Austrian gross domestic product (GDP) or, expressed in absolute numbers, for up to 12.38 billion € (3.1% of Austria's GDP in 2019; WKÖ, 2019, p. 2). According to a French study the total costs due to such leaves on company level within the manufacturing industry were estimated to account for 6,800 to 11,200 Euros per affected worker and year (EUOSH, 2010b, p. 100).

[1] Compare e.g. Oliv *et al.* 2017; Fejer *et al.* 2006; Borg and Hensing 2001; Hoy *et al.* 2010; Hoy *et al.* 2014; Hansson and Hansson 2005; Van Rijn *et al.* 2014; NRC/IM, 2001; Stock *et al*. 2011 from Chiasson *et al.* 2015, Kemmlert and Lundholm 1994; Shahnavaz 1987; Genaidy *et al.* 1993; Tsauo *et al*. 2009; Neumann 2004; Punnet *et al.* 2004; Eashw 2008; Choobineh *et al.* 2011 cited from Varianou-Mikellidou *et al.* (2019, p. 239).

	Days of incapacity for work		Production downtime costs		Loss of gross value added	
Diagnosis group	Million	%	Billion €	% GDP	Billion €	% GDP
Diseases of the musculoskeletal system	150.4	21.8	17.2	0.5	30.5	0.9
Psychological and mental disorders	107	16	12.2	0.4	21.7	0.7
Diseases of the respiratory system	92.9	13.9	10.6	0.3	18.8	0.6
Injuries, poisonings and accidents	70.2	10.5	8	0.2	14.2	0.4
Diseases of the circulatory system	34.1	5.1	3,9	0.1	6.9	0.2
Diseases of the digestive system	33.5	5	3.8	0.1	6.8	0.2
Other diseases	180.5	27	20.6	0.6	36.6	1.1
All diagnosis groups	668.6	100	76.3	2.2	135.5	4.1

Figure 5: Direct and indirect costs of occupational diseases in Germany (BAuA, 2017, p. 2)

In conclusion, MSD are a diverse group of conditions which affect the musculoskeletal system and are associated with pain and impaired physical function (Seeberg *et al.*, 2019, p. 2). They are one of the main factors that cause working days lost, disability pensions early retirement (Varianou-Mikellidou *et al.*, 2019, p. 239; Landau *et al.*, 2008, p. 562). MSD can be seen as a major burden on individuals, the health system and social care systems, causing majorcosts with pervasive impacts (Woolf and Pfleger, 2003). As MSD is considered especially, as a problem for elderly workers, these figures are projected to further increase due to an increase in retirement ages and an increase in workers aged 50 years and older, caused by the ongoing demographic change in most developed countries (Jawad et al. 2019, p 234).

1.1.3 Potential solutions for industry – supporting technologies and workplace design

One suitable measure to reduce work stresses and related health risks as mentioned above, would be full automation. However, this is currently not possible and will not always be feasible in the near future. For instance, in dynamic manufacturing, warehousing environments, or in production systems with a high product mix and small order sizes, which require a high level of flexibility, full-automation is either not possible or prohibitively expensive (DeLooze *et al.*, 2016, p. 671). In the context of continuously varying products and tasks, the human capacity to observe, decide and adopt proper actions within seconds, is required (DeLooze *et al.*, 2016, p. 671). Due to the human flexibility and creativity as well as the ability to reason and to decide based on intuition, which can and will not be fully replaced by autonomous systems, the human will play a central role in current and future factories (Günthner *et al.*, 2014). Logistics and production are two examples where human presence will stay essential to compensate for technological limitations and to provide the most benefits for productivity, reliability, economy and flexibility (Gehrke *et al.*, 2015, pp. 1–28). In such systems human labour along with operating resources and materials, is one of the elementary factors in the value creation process (Gutenberg, 1983). Thus, workers will still be exposed to various production activities, such as assembling or material handling (DeLooze et al. 2016, p 671) in the near future and, to reduce the associated risks of developing MSD, it is crucial to provide age-appropriate workplaces. Therefore, an adaption of the workload to prevent health issues as described before is necessary.

The cause-effect relationship between the experienced workloads, and the resulting individual strain on employees is represented in the stress-strain concept (Rohmert, 1984). Based on this concept, the resulting strain is determined by the amount or magnitude and duration of stress, in relation to the individual abilities of the employees (Rohmert and Rutenfranz, 1983; Rohmert, 1984; REFA, 1984). As physical abilities in particular are subject to an age-related decrease (Kenny *et al.*, 2008), an increase in the strain of older employees can be assumed according to the model, if the physical work stress remains constant. Using the stress-strain concept can help to identify workplaces that require measures in order to adapt their stress to the age-related change of abilities.

Worker-centred work design attempts to fit the workplace to its individual worker to avoid incorrect loading and health risks. Technical development of the recent years summarized under the umbrella term “Industry 4.0” or “advanced manufacturing” offers new possibilities to assist the workers at shop-floor level. Inside a smart manufacturing environment, a set of connected devices and intelligent systems collaborate with humans, without replacing, but empowering them and enlarging their abilities (Kusiak, 2018; Calzavara *et al.*, 2019, p. 7). Future work systems are envisioned to be characterized by highly complex, varying and knowledge-intensive work processes, where the worker more than ever will be in need for support and technological assistance (Wolf *et al.*, 2018, p. 67). In order to maintain and increase per capita productivity in the increased use of automation and technologic innovation appears to be unavoidable and a suitable mixture of human and machine work is required (Bley *et al.*, 2004, p. 495).

Human-machine-interaction is a key element of industrial automation. Through technical innovations, the performance, skills and flexibility of this solutions is constantly growing, making them suitable for an increasingly broad range of applications and industries (Spillner, 2014, p. 3). The advantage of such a human-technology-cooperation is seen in the fact that humans are able to use their experience and decision-making competence, thus overcoming technological limitations of isolated technical solutions. At the same time, the technology can relieve people of physically demanding, tiring or dangerous tasks by physical and cognitive support (Krüger *et al.*, 2009), thus lowering the overall work strain for the worker. However, the economic optimum does not lie in maximising the degree of automation (Lay and Schmeister, 2001, p. 4). In volatile markets, the exclusion of the experience and flexibility of humans leads to high flexibility costs, so that a suitable mixture of human and machine work is required (Bley *et al.*, 2004, p. 495).

For dynamic working environments where physical work tasks have to be executed by humans, particularly elderly workforce will be in need of physical assistance (Calzavara *et al.*, 2019, p. 12). Within this domain, especially body worn assisting systems are seen as a potential new measure to firstly reduce physical stress, secondly keep workers healthy by improving working conditions, and thirdly to compensate for decreases in performance (Dahmen *et al.*, 2018b, p. 268; EUOSH, 2019a, 2019b; DeLooze *et al.*, 2016). Therefor these systems can be used to design age-appropriate stress situations and workplaces and f this type of technology particularly appears to be a suitable measure to counter industrial demographic challenges in physical work.

1.2 RESEARCH MOTIVATION

As outlined previously the demographic challenges are of increasing importance for the economy of European countries, their member states, and the companies responsible for generating their GDP. In relation to the increase in MSD and related sick leave in older workers, in combination with the average population ageing, especially in the industry branches involving a high proportion of manual work, new concepts in work design and individual adaption are demanded in order to be able to ensure the value-adding deployment of elderly employees in the future. Several assessment systems to identify physical overloading are applied in industrial work design, however, specifics of an ageing workforce are not considered correctly.in an adequate way. Besides the classical approach of isolated stress reduction, also the control of the individual work strain promises to be a suitable solution for the ageing workforce. For the individual adaptation of strain new possibilities derive from technological developments in physical assistance systems. However, for such technologies, a low level of scientific reliable results and no structured approaches for their application in industry are currently available. This is where this thesis aims to contribute to the scientific literature and the occupational practice in industry.

1.3 OBJECTIVE OF THE THESIS

The aim of this work is to describe systematic workplace improvement in relationship to an ageing workforce as a holistic approach and to operationalize it to an extent that it can be implemented in industrial companies. To this end, a structured approach is being developed that will allow the integration of systematic workplace improvement. Thus, the objective of this thesis is to develop a process model that enables the systematic identification of workplaces with age-critical work stresses and its minimization by the use of assisting technologies at industrial workplaces. The targeted use of physical assistance technologies for levelling age-differentiated work strain in production and logistics has not yet been examined in detail. A number of prerequisites have to be created for such an application:

First, a procedure is required which enables a targeted identification of age-critical work stress. Therefore, age-critical workplaces must be identified considering the differences in young and older workers in relation to relevant abilities and deriving work strain. The second task is to identify systems for age-based assistance. To identify such technology based on work stress and strain a structured process is needed that compares the assistance provided by technologies to the assistance needed at existing at workplaces in relation to ergonomic assessment results. Third, an overview of the possible applications of age-based assistance and an evaluation of the respective application potential must be carried out to identify suitable solutions. Moreover, a structured procedure for the identification of suitable technologies has to be generated. Lastly, a structured approach for the planning of technology application is needed. Such planning is facilitated if a larger selection of systems and modules is available for assistance and successful application examples are known. Therefore, an approach for the evaluation of stress and strain related outcomes of applying these technologies is needed.

The research in this study aims to contribute to both, industrial practice and scientific research. Therefore, the research leading questions were formulated, so that they were of interest for the companies concerned and for academia alike. According to the objective of this study the research leading question is formulated as:

“What steps have to be conducted to improve workplaces for elderly workers in selected industries and how can physical assistance technologies help in designing age-appropriate work places?”

1.4 BACKGROUND OF THIS STUDY

The thesis is the result of an industrial research project. This project was funded by the Austrian Research Promotion Agency (FFG) and took place form June 2017 until June 2020. Besides the lead partner, the Institute of Innovation and Industrial Management at Graz University of Technology, two industrial partners participated in the project. One partner was selected out of the manufacturing industry. This partner mainly produces heavy machinery as trucks and equipment for firefighters. The second partner was selected out of the complimentary field of food retail, to increase result transferability. The research cooperation was established as a result of a pre-study conducted by the author of this thesis. This pre-study was carried out as a master’s thesis project in 2016 identifying different needs for action in Austrian regulations and international standardization in relation to an ageing workforce and Industry 4.0. Based on this results and the industrial requests for application-oriented research a funding proposal was prepared by the author of this thesis and approved by the FFG in May 2017. The timeline of the research project, related work packages and their content are summarized in Figure 6.

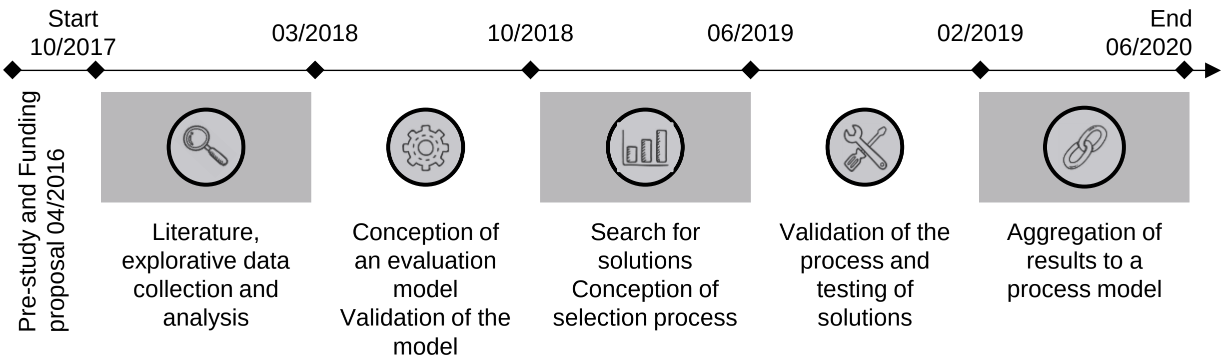

Figure 6: Overview of the timeline of the research project and related content of work packages

1.5 THESIS OUTLINE

Throughout chapter 1 the motivation of the thesis resulting from demographic change and related health problems has been described. The relevance of the topic was pointed out from a scientific, and economic-industrial, point of view.

In chapter 2 existing knowledge considering connections between health, workability and ageing is summarized. Further, basic knowledge about ergonomic workplace design and existing models for age-appropriate workforce deployment is outlined. Moreover, current development in the area of technological worker assistance and assisting systems are briefly introduced. Finally, based on an interim conclusion of the existing knowledge, the research need from a scientific point of view is derived and requirements for the process model are named.

Chapter 3 consequently deals with the derivation of the objectives of the thesis, as well as with the deduction of the relevant research questions and the description of the intended contribution. Further, the research area is limited and the focus of the thesis is named.

In chapter 4 methodological considerations are drawn. A research framework is derived, the research design is explained and the research process described. Further, the focus of the study is narrowed down.

Chapter 5 describes the field study conducted to identify implications from industry for age-appropriate workplace design. Based on the data collected with different methods requirements for the tool and procedure model to develop are derived.

In chapter 6, based on model theoretical considerations, the newly developed procedure model and the process for its application is presented.

Chapter 7 deals with the conception of the newly developed approach. Besides the explanation of methodological-, model-theoretical- and system-theoretical aspects, general factors considering evaluation criteria, and procedure models are stated. Subsequently the contents of the different parts (building blocks) of the procedure model are derived and explained. The developed methodology and tool for age-differentiated ergonomic workplace assessment is introduced. The gathered information about measures to provide age appropriate work situations is summarized in a newly developed ergonomic intervention framework for practical application. The process for identifying suitable solutions is explained and last, a methodology to evaluate ergonomic interventions in relation to benefits for age-appropriate strain reduction is introduced.

Chapter 8 concludes and discusses the outcome of the thesis. A summary of the results is provided and the practical and scientific outcomes are described and critically discussed in terms of validity and reliability. The thesis closes with an outlook chapter with suggestion for further research. Figure 7 summarizes the content of this thesis and related outcomes of the chapters as listed above.

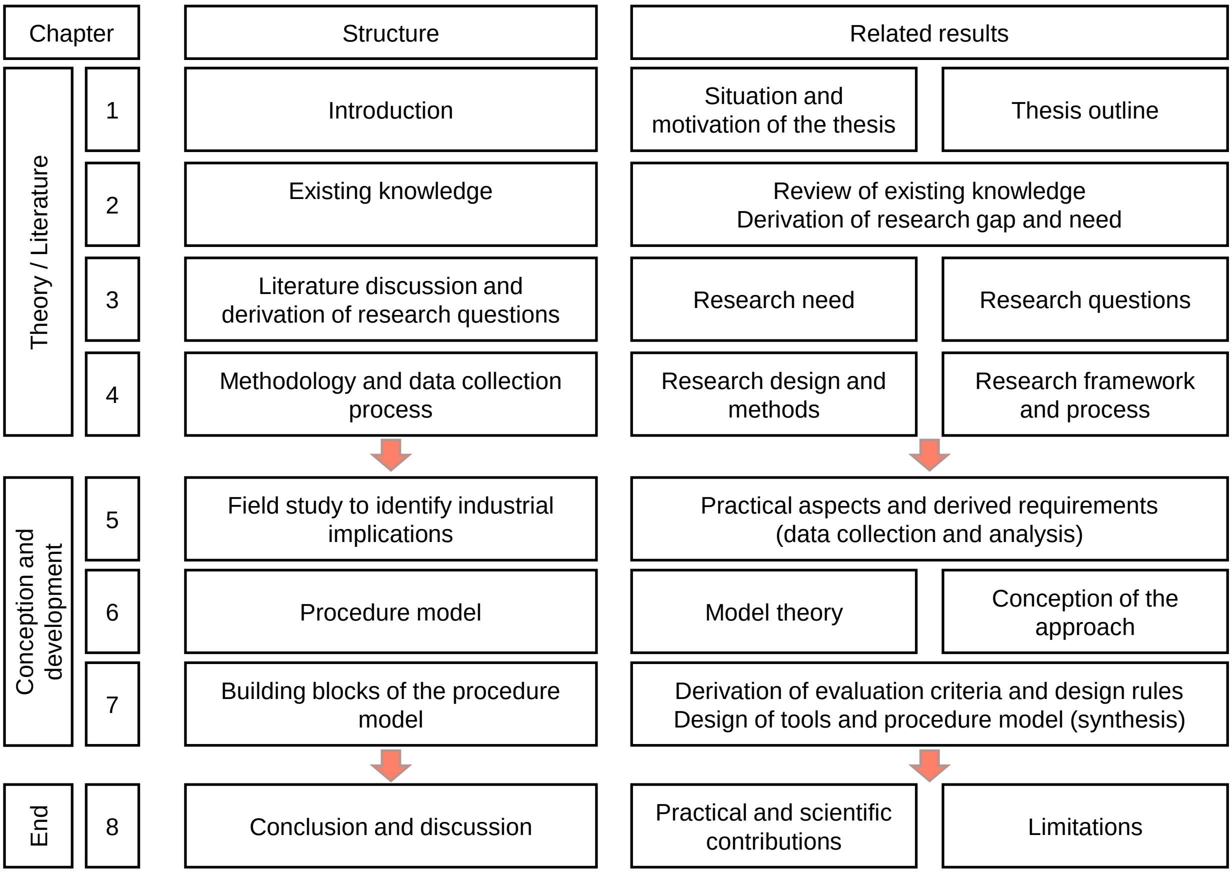

Figure 7: Structure of the thesis and related results

2 EXISTING KNOWLEDGE

In the introductory section the main fields of interest for this thesis were outlined. Based on this initial problem statement, this chapter is aimed at deepen the understanding of the scientific knowledge on general characteristics of ageing and derived industrial implications. Therefore, related theory is summarized. Based on scientific findings of cause-effect relations of developing MSD, the first section explores their relation to industrial work stress. Consequently, the second part deals with the influence of human factors towards this topic. As a main influencing factor, individual abilities and general effects of aging on these are elaborated in detail. The first interim conclusion summarizes existing problems of elderly workers in industrial work settings. After identifying the relevant problems, an overview of possible solutions within the ergonomic work design process is provided. Both parts of the process, the ergonomic assessment of work stress and the ergonomic improvement process are highlighted within this section. Beside general solutions, a focus is put on the potential role that assistance systems can take in the design of age-appropriate work design. To achieve this, existing concepts for the derivation of the need for assistance and the identification of suitable technical solutions is reviewed. The second section ends with an interim conclusion on existing approaches to deal with challenges of elderly workers in industry. Based on the summary of the existing knowledge, the related research need is concluded.

2.1 SCOPE AND FOCUS OF THE DISCUSSED LITERATURE

An extensive literature study was conducted to develop a sound understanding of related research. This is necessary to position the research in relation to existing knowledge and to develop a holistic understanding of common tools in industrial practice as needed in application-oriented research approaches (Edmondson and McManus, 2007, p. 1173).

The study at hand deals with an interdisciplinary topic incorporating the scientific fields of medical, ergonomic, industry-related and social sciences. The main clusters to be considered in the analysis of existing knowledge were defined to encompass musculoskeletal disorders as the main problem of sick leave in relation to age (see section 1.1.2) and industrial work that consist of mainly physical work, as a major cause for developing MSD (see section 1.1.1), physiological and physical human abilities as a prerequisite for physical work and the implications of ageing, as a mediator, on this topic. As current industrial practice seems not to be a suitable approach in relation to age-related problems, the study focuses on new technological possibilities for individual support by means of physical assisting systems (see section 1.1.3). This defines the scope of the literature analysis whereby particular focus was put on academic literature located in the intersection of the different fields.

2.2 HUMAN FACTORS IN INDUSTRIAL WORK

This chapter summarizes existing knowledge in terms of health outcomes of physical work in relation to stress and strain. After defining the most important concepts and terms, musculoskeletal disorders and their occurrence in different occupations is described. Further, age-related changes of human resources (abilities, skills, attitudes etc.) are described. Subsequently ability changes for industry relevant abilities are quantified based on literature and finally implications for proper workplace design are drawn.

2.2.1 Workload in relation to the work system

In a general industrial work system, input in the form of energy, material, information and human labour is transferred into outputs in the form of finished products or services. For this purpose, the human interacts with operating resources and work objects within and under the influence of environmental conditions, to control the transformation process (Schlick *et al.*, 2010, pp. 35–36). Based on the factors involved in the operational performance several hazards can occur. A hazard is defined as the possibility of the occurrence of damage or impairment of health without a specific statement about the extent or probability of the occurrence (ÖNORM EN ISO 12100, 2013, p. 7). As shown in Figure 8, a total of 11 hazard groups can be distinguished according to the general hazard classification. (GDA, 2008)

1	**Mechanical hazards**	1.1 Unprotected moving machine parts	1.2 Parts with dangerous surfaces	1.3 Mooving transport and work equipment	1.4 Uncontrolled moving parts	1.5 Falling, stumbling, slipping, kinking	1.6 Crashing / Falling	
2	**Electronic hazards**	2.1 Electric shock	2.2 Electrical arc	2.3 Electrostatic charges				
3	**hazardous substances**	3.1 Skin contact with hazardous substances	3.2 Inhalation of hazardous substances	3.3 Ingestion of substances	3.4 Physico-chemical hazard			
4	**Biological working materials**	4.1 Infection hazard by pathogenic microorganisms	4.2 Sensitizing and toxic effects of microorganisms					
5	**Fire and explosion hazard**	5.1 Combustible solids, gases, Liquids,	5.2 Explosive atmosphere	5.3 Explosives				
6	**Thermal hazards**	6.1 Hot media / surfaces	6.2 Cold media / surfaces					
7	**Special physical factors**	7.1 Noise	7.2 Ultrasound, Infrasound	7.3 Whole-body vibration	7.4 Hand-arm vibrations	7.5 Optical radiation (UV, IR, laser)	7.6 Ionizing radiation (e.g., X-rays)	7.7 Electro-magnetic fields
8	**working environment**	8.1 Climate (heat, cold)	8.2 Light	8.3 Suffocation or drowning				
9	**Physical work load**	9.1 Heavy dynamic work, combination of static and dynamic work	9.2 Unilateral dynamic work, body movement	9.3 Holding work + Postural work (forced postures)	9.4 Load handling	9.5 Repeating uniform movements (finger-hand-arm, foot-leg)	9.6 Working while sitting, standing, or walking, squatting, kneeing, or lying	
10	**Mental and psychological factors**	10.1 Inadequately designed work task	10.2 Inadequately designed work organization	10.3 Inadequately designed social conditions	10.4 Inadequately designed work-places and environments	10.5 Dequalification, outdated knowledge, learning cessation		
11	**Other hazards**	11.1 By animals	11.2 Through plants + herbal products	11.3 By people	11.6 Human - machine cooperation			

Figure 8: General hazards classification (adapted from BGHM, 2016, pp. 14–15)

According to Figure 8 a multitude of health hazards can exist within work systems, deriving from the operating resources and work objects (mechanical, electrical, thermal, substances, material) and the work environment (physical influences as noise, climate, lighting, vibrations, etc.). In addition, physical and psychological factors can expose the human operator to health risks (BGHM, 2016, pp. 14–15). The sum of these external conditions that affect the physiological and psychological state of a person at work is defined as the workload (ÖNORM EN ISO 6385, 2016). Workloads are composed of partial loads that can occur in parallel or sequentially, and can be specified according to their intensity and duration (Bokranz and Landau, 1991, p. 35; Schlick *et al.*, 2010, p. 40).The partial loads can derive from the working environment, the man-machine interface, the work organisation, or the work task (ÖNORM EN ISO 6385, 2016).

2.2.2 Work stress in relation to the work environment and human-machine interaction

Stress from the work environment can occur due to the environmental conditions including climate, noise, vibrations, lighting (VDI, 1980, p. 22). Main factors for work stress due to exposure to climate are thermal conditions, acoustic environment, and visual settings (EN ISO 11399, 2000). The climatic stresses depend on the parameters air temperature, air humidity, air speed, heat radiation, work load and clothing (DIN EN ISO 28802, 2012). Sound is defined as vibration in gases, liquids or solid materials (VDI, 1980, p. 115). Work stress can be caused by noise produced by machines or processes (Schlick *et al.*, 2010, p. 778). In industrial environments, noise levels below 80 dB should be maintained (EN ISO 11690-1, 1997). The main factor within the visual setting is the lighting of workplaces, which should be adapted to the work activities (VDI, 1980, p. 136) as stress can derive from unsuitable lighting conditions (REFA, 1984, p. 248; ÖNORM EN 12464-1, 2011).

An additional factor located in the work environment section is the machinery used by the workers. The human-machine interface comprises all components of a system (software and hardware) that provide information and controls necessary for the user to perform a specific task with the interactive system (EN ISO 9241-110, 2008). This includes information input via switches, buttons or levers as well as information output, e.g. via displays on screens/control stations or the acoustic or visual feedback of system states (EN ISO 9241-110). Work stress due to the human-machine interface can result, from missing system feedback or problems with information output (EUOSH, 2010a, pp. 17–18).

2.2.3 Work stress in relation to the work organisation

Work organisation refers to the planning and design of workplaces (Schlick *et al.*, 2010, p. 436). Work stress due to work organisation, can exist in relation to regulation of working time, way of sequencing activities, work flow and the type of cooperation (BAuA, 2010, p. 9). Stress can arise, from shift work, division of labour, time and space constraints and limited communication (Bokranz and Landau, 2012, p. 174).

Shift work can result in stress due to the location of the working time. Especially in night shift when the physiological performance is low (Bokranz and Landau, 2012, p. 174), as well as due to a lack of contact and communication possibilities with the social environment (Martin, 1994, p. 198).

A strong division of labour, in which complex work tasks are divided among several people or machines, is characterised by repetitive work processes with short cycle times and high repetition frequency and low requirements (Schlick *et al.*, 2010, p. 506; Bokranz and Landau, 2012, p. 174). A strong division of work can result in a one-sided physical and psychological work strain as well as the loss of qualification (Schlick *et al.*, 2010, p. 630).

Time and space constraints as a stress factor emerge in interlinked work systems. In such systems employees are often closely bound to a fixed working rhythm determined by the machine cycle or the work group and also spatially tied to a work place (Martin, 1994, p. 314). The missing or at least strongly limited possibility of a self-determined division of the work activity and communication with other persons can have an emotionally stressful effect (Bokranz and Landau, 2012, p. 174). Social working conditions relate to the possibility or requirement of communication and cooperation relationships at work (Martin, 1994, p. 182). Stress can derive as a consequence of lack of communication and cooperation (social isolation) in connection with low work requirements and a lack of recognition and inclusion can result in psychological saturation and frustration (Bokranz and Landau, 2012, p. 175).

2.2.4 Work stress in relation to the work tasks

Task-related exposure types are related to the physical activity and can be divided into energetic and informational exposures. Informational stress is related to mental work and is influenced by the difficulty of information processing. Energetic work, on the other hand, acts as physical stress on the skeletal muscles. The occurrence of physical and mental stress in parallel, is defined as sensomotoric activities, which require coordination between motor and sensory functions. (Schlick *et al.*, 2010, pp. 223–224) Therefore, work can be divided in physical and mental tasks, whereas either the muscular and sensomotric stress or the mental stresses prevail. In Table 1 different types of work are summarized including the characteristics of the work tasks, the human resources needed and a practical example.

Table 1: Types of work [adapted from (Schlick *et al.*, 2010, p. 224)]

Type of work	Physical and energetic		Informatory and mental		
	Muscular	Motoric	Reactive	Combinative	Creative
Characteristics of work tasks	Exertion of muscular forces. Mechanical work	Movements of hands, arms with a certain degree of precision. No high forces needed	Reception and processing of information, and execution of reaction	Reception, processing, and transformation of information. Linking information to memory content	Generation of information and, transmission of information into a new context
Stress on organs	Muscles, tendons, circulatory system, respiration, skeleton	Muscles, tendons, sensory organs, circulatory system	Sensory organs, muscles, cognitive capacities	Sensory organs and cognitive capacities, muscles	Cognitive capacities
Example	Manual material handling, lifting	Repetitive manual work as assembly	Driving, inspection	Programming	Inventing, problem solving

Mental work can be subdivided according to Luczak (1975) in three steps, the information acquisition, the information processing and the execution of a reaction. The information acquisition involves the discovery of a stimulus by means of sensing organs. The information processing describes the recognition of the signal`s meaning, the identification of its essential features and the deciding between action alternatives. Lastly a reaction through motor regulation and information delivery is carried out (Schlick *et al.*, 2010, pp. 226–227).

2.2.5 Ergonomic basics of physical work

A classification of physical work can be conducted in relation to type of movement and magnitude of load (see Figure 9). Thus, tasks can either involve low or high loads, and be of static or dynamic nature.

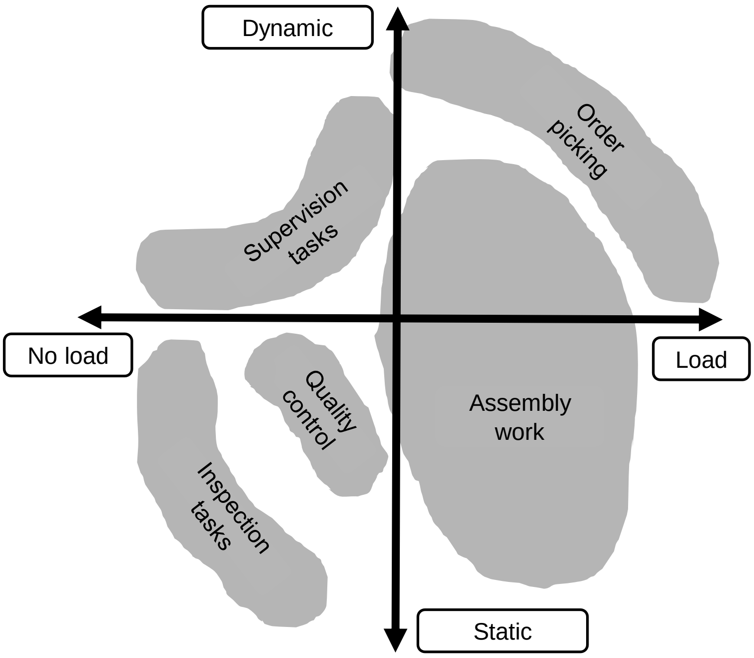

Figure 9: Classification of work within four areas with examples (cf. Klabunde and Weidner, 2018, p. 456)

Tasks with a low load are tasks where components or tools with a low weight are handled or work tasks typically included in maintenance work and inspections or supervision activities are carried out. While inspection and control tasks have more of a static nature, supervision tasks contain more dynamic tasks

(Klabunde und Weidner 2018, S. 455–457). Therefore, working postures are the main factor to consider when designing such work places.

Activities with a significant load impact occur in an industrial work setting mainly in order picking activities and assembly tasks. In order picking, lifting, and manual material handling, as in the case of pick and place operations and loading of pallets or similar tasks, cause the main stress factor for the worker (Prasch, 2010, p. 24). Further, in such activities dynamically alternating upright and bent postures have to be taken with a high repetition rate (Klabunde and Weidner, 2018, pp. 455–457; Walch, 2012, p. 79). A study by Walch showed within a case study in industry, that especially in order picking high ergonomic risks are present in relation to bending activities for about 60% of the 28 workplaces included. Further, a risk for manual material handling tasks was identified at over 70% of the workplaces studied (Walch, 2011, p. 79). The dynamic work results in high stress mainly regarding the leg, shoulder and whole back region (Walch, 2011, p. 81). Therefore, ergonomic postures and the attributes of the load handling processes are important in the design of such workplaces. In addition to physical stress, the two environment factors of whole-body vibrations and climatic influences such as temperature fluctuations are particularly prevalent in logistics work. (Hentschel *et al.*, 2012, p. 402) In assembly work physiological performance parameters are characterized by one-sided dynamic muscle work in connection with sensorimotor tasks (Egbers, 2013, p. 14). Nevertheless, the handling of products or tools can also include manual handling of heavy loads (Prasch, 2010, p. 45; Punnett and Wegman, 2004, p. 14). But in contrary to order picking, most work tasks are carried out in defined work postures that a maintained over a longer period of time (Klabunde and Weidner, 2018, pp. 455–457). A study by Buck 1995 including 464 workplaces for line assembly showed that about 35% of assembly work places are characterized by one sided dynamic work and slightly over 50% include unfavourable working postures (Buck *et al.*, 1995, 403). Therefore, every (assembly) activity at a fixed location implies a certain amount of static work. The static work often lead to high stress for the legs and the lower back (Wittemann, 2017, p. 14). Thus, postural work is an important factor to consider when designing assembly work places. A comprehensive descriptions of typical workloads depending on the type of assembly organisation can be found in (Prasch, 2010, pp. 65–71).

2.2.5.1 Static muscular work

In relation to the classification according to the degree of involved movements, tasks involving few or no movements belong to the category of static work (Schlick *et al.*, 2010, p. 225; Bokranz and Landau, 1991, p. 116; Bokranz and Landau, 2012, p. 135). Static work can further be divided in postural work and holding work (Nordin and Frankel, 2008, 149, 159; Bokranz and Landau, 2012, p. 116). Static postural work is defined as a reaction to body-internal forces (i.e. maintaining a working posture) and static holding work is needed to counterbalance external forces, as needed when holding a tool (Schlick *et al.*, 2010, p. 231; Bokranz and Landau, 2012, p. 136). In static work the constant contraction of a specific muscle area reduces the blood circulation in the affected body parts resulting in an undersupply of oxygen and nutrients, what quickly leads to fatigue in the involved muscles (Schlick *et al.*, 2010, p. 225; Bokranz and Landau, 2012, pp. 135–136). Therefore, from a physiological point of view, static work tasks requiring static muscular work are particularly problematic. In Figure 10 an overview of predominantly physical work is illustrated, also showing the ratio of blood required and supplied for the different types of muscular work.

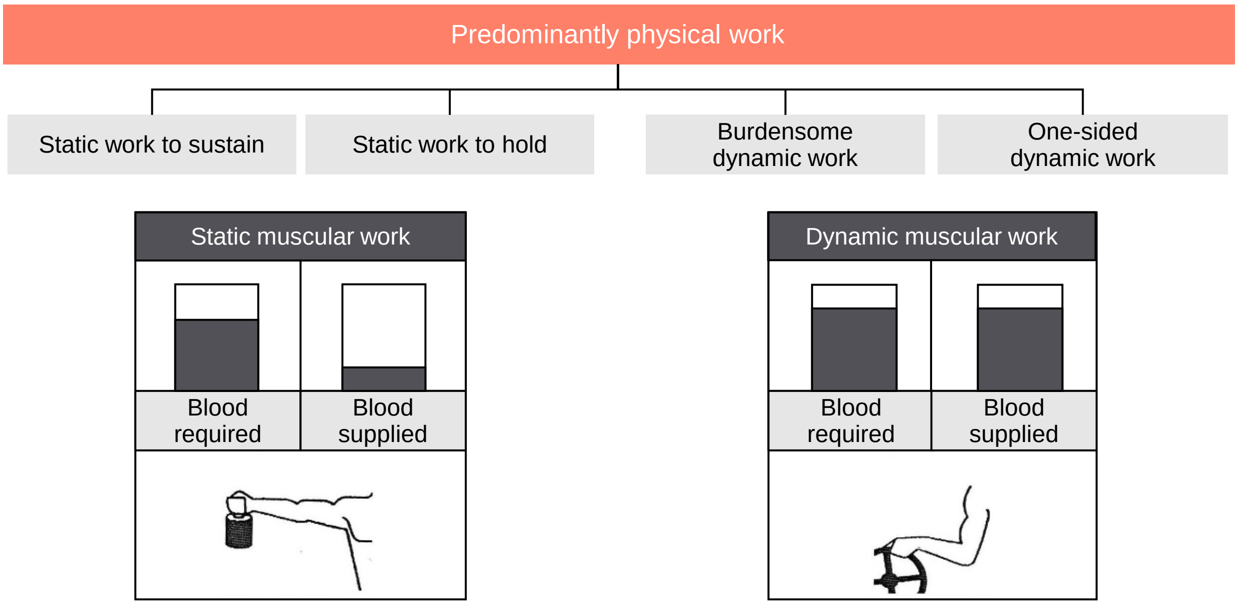

Figure 10: Types of physical work and related limiting factors (Schlick *et al.*, 2010, p. 232)

Static work with the aforementioned problem in terms of blood supply is therefore always perceived as more straining than dynamic work (Bokranz and Landau, 1991, p. 135). Further, only about 15% of the maximum force of a muscle can be maintained without fatigue in static work (Rohmert, 1983). At a higher load as 15% of the maximum force, the endurance declines rapidly with an increasing force to about four minutes at 25% and one minute at 50% of the maximum force (Schlick *et al.*, 2010, p. 232).

Further, static work also stresses bones, joints, tendons and ligaments. The stress put on here is mostly neglected, as the related pain receptors have a high sensitivity threshold. Therefore, only extremely high stresses can be felt in the passive elements (Schlick *et al.*, 2010, p. 232). For the reduce in muscle endurance and the health impairing effects on the human passive system, it is only of secondary importance whether holding work or postural work is to be carried out caused by the unchanged inner loading (Schlick *et al.*, 2010, p. 957). Therefore, either for holding an object or for maintaining a specific body position a certain amount of static muscular work (Bokranz and Landau, 2012, p. 135). According to Hartmann *et al.*, 2013, the body postures especially have stressful effect on the person if the work is carried out in a forced posture. Typical forced postures are work with a bent back, particularly when standing bent-over, kneeling or squatting, forced standing for a prolonged period of time, forced sitting postures or activities above shoulder or head level (Hartmann *et al.*, 2013, pp. 3–5).

In the context of work design, this means that any kind of static muscle work should be avoided if possible (Schlick *et al.*, 2010, p. 957). Accordingly, changing the posture within a certain range and break times must be provided to prevent overexertion (Schultetus, 1987, pp. 18–20). If the static holding of objects is unavoidable, it should be designed to keep the mechanical momentum as small as possible (Schlick *et al.*, 2010, p. 957). An important task in work design is also in the preventive protection against postural stresses, before the stress limit is significantly reduced due to illness or damage (Schlick *et al.*, 2010, pp. 232–233).

2.2.5.2 Dynamic muscular work

If a higher level of movement is necessary, the work is classified as dynamic work (Nordin and Frankel, 2008, p. 159; Bokranz and Landau, 2012, p. 137; Bokranz and Landau, 1991, p. 118). A distinction is made according to the proportion of total muscle mass used. In heavy dynamic work a high proportion is used (Schlick *et al.*, 2010, p. 230; Bokranz and Landau, 2012, p. 137). In one-sided dynamic work, only small muscle groups are used, where (local) fatigue in the muscle is the limiting factor (Schlick *et al.*, 2010, p. 225; Bokranz and Landau, 2012, p. 137; Bokranz and Landau, 1991, p. 118). In dynamic work, alternating tension and relief of the muscle leads to an increased blood circulation in the muscle up to the 20 fold compared to relaxation (Bokranz and Landau, 2012, p. 137). Therefore, the bottleneck is defined by the cardiovascular and respiratory system for this type of work (Bokranz and Landau, 1991, p. 118).

Dynamic work mainly stresses the muscular-skeleton system, the cardiovascular system and the metabolic system (Schlick *et al.*, 2010, p. 230). In dynamic work a differentiation can be made according to the muscle mass in use. In heavy dynamic work several (more than one seventh of the total muscle mass) and usually large muscle groups are involved simultaneously (Bokranz and Landau, 1991, p. 118). At high exertion, the limited performance capacity of the cardiovascular system primarily leads to a supply bottleneck (Schlick *et al.*, 2010, p. 230). This heavy physical work result in a permanently increasing circulatory load (Schultetus, 1987, pp. 18–22). One-sided dynamic work is present when small muscle groups are used with a relatively high frequency of movement, as present in repetitive sensomotoric work (Bokranz and Landau, 2012, p. 137). These activities do not lead to extraordinary fatigue and are characteristic for the manual activities in line assembly (Prasch, 2010, p. 24). The maximum possible working time is mainly limited by the working capacity of the muscle (VDI, 1980, p. 35; Martin, 1994, p. 102)

Summing up: stress can be determined as the sum of the objective demands on the human being by various measurable variables and qualitatively describable stressors, which result from the task, the conditions of execution and the environmental conditions and which act on the human being as external factors.

2.2.6 Work strain as the related human reaction on stress

Work stress described in the previous section is understood as the external characteristics of the work situation and is seen as a neutral factor in work science (Schlick *et al.*, 2010, p.38, p.59). Therefore, physical work stress is neither positive or negative by itself (Bokranz and Landau, 1991, p. 260). Strain is defined as the internal reaction of the human with its individual characteristics to the external stress or workload (ÖNORM EN ISO 6385, 2016). Strain is dependent on the individual resources as physical attributes, abilities, experience, motivation etc. (Schlick *et al.*, 2010, p. 39). Further, the individual factors can also be variable during the period of task execution (Schlick *et al.*, 2010, p. 393). As these individual resources differ in between different persons as well as within a person in different points in time the exposure to the same stressor results in different reactions (Bokranz and Landau, 1991, p. 32; REFA, 1984, p. 161)

In terms of strain a differentiation is made in physical, mental and emotional strain (Schlick *et al.*, 2010, pp. 293–294). Physical strain describes the effects of stress on the muscle and circulatory system (Kirchner, 1986, pp. 555–556). Strain reactions resulting from physical stress are objectively measurable by means of physiological parameters such as heart rate, respiratory rate, respiratory volume, blood pressure, body temperature etc. (Schlick *et al.*, 2010, p. 293). Mental strain is defined as the effect of mental stress on the individual, depending on his or her precondition, including individual coping strategies (ÖNORM EN ISO 10075, 2018). Mental strain is a combination of strain arising from information reception, processing, decision making and reaction provision (Kirchner, 1986, pp. 556–557). Mental stress thus results from the interaction of internal and external factors, whereby the external factors are of human-machine interaction are determined in particular by properties of the technical system (Schlick *et al.*, 2010, p. 394). Finally, emotional strain is the reaction of the human to execution of work and environmental conditions such as time pressure, noise, climate or interpersonal relationships (Kirchner, 1986, p. 556). Emotional strain influences motivation and can lead to feelings like boredom, fear, helplessness (Schlick *et al.*, 2010, p. 394; Bokranz and Landau, 1991, p. 264). A special manifestation of emotional strain is emotional stress as a stress-reaction, which results in physiological reactions and therefore can be measured (Kirchner, 1986, p. 557).

Similar to stress, strain is defined as a neutral factor in work science (Bokranz and Landau, 1991, p. 260). A basic level of strain and therefore stress is needed to maintain the performance prerequisites (Bokranz and Landau, 1991, p. 193). If the stress exceeds the individual resources positive and negative consequences can result (Laurig, 1992, p. 40). If the exceeding is short term and low, besides fatigue as negative effect, also training for physical skills or practice for mental tasks of the related performance prerequisite take place (Bokranz and Landau, 1991, pp. 187–192). If the strain exceeds the reference level long term or by a high amount, only negative effects in term of health impairments emerge (Münzberger 2005 cited from Walch and Günther, 2009, p. 35; Schlick *et al.*, 2010, p. 42). In terms of work design, a distinction must be made between the desired or undesired effects and the conditions that can cause and in some cases influence these effects. Therefore, the stress-strain concept according to Rohmert (1984) offers a corresponding approach that shows the relationships between the work situation and the effect on the worker as shown in Figure 11.

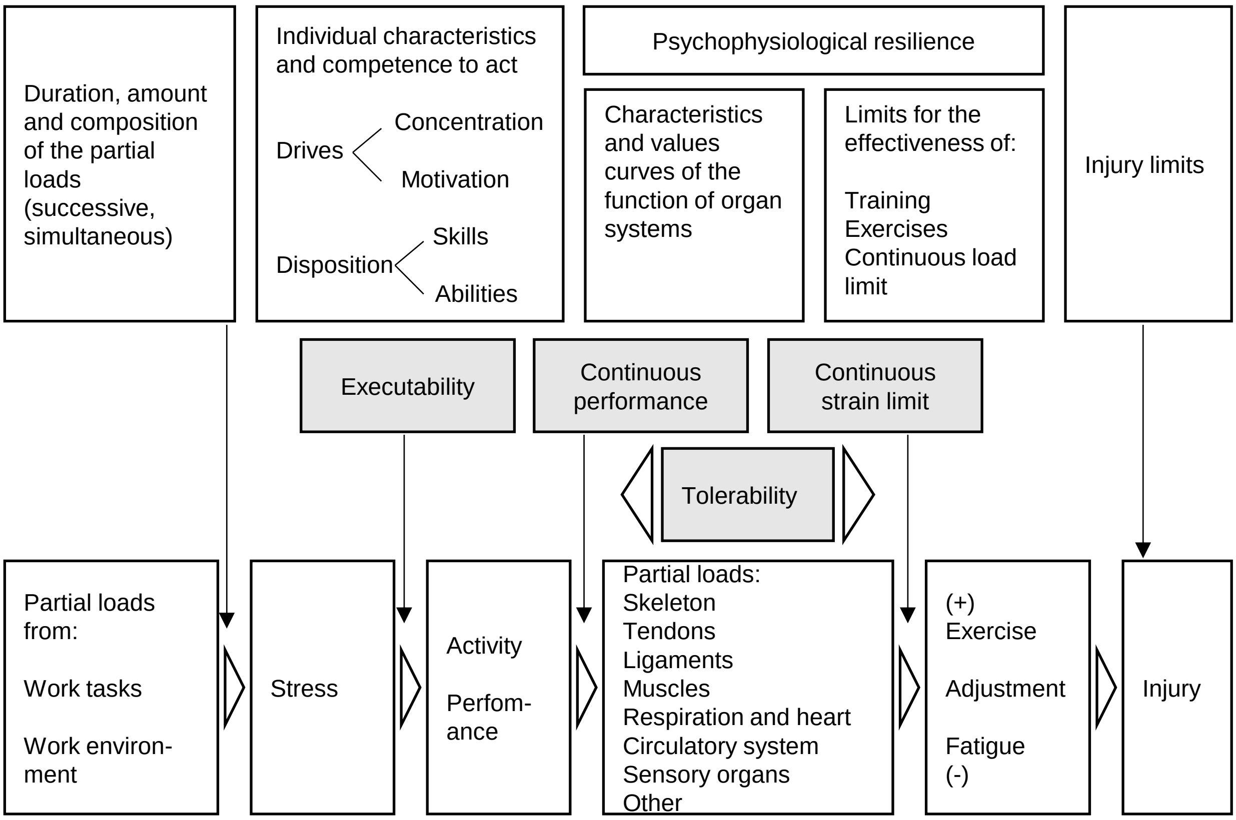

Figure 11: Extended stress-strain concept (Luczak 1975 and Rohmert 1984 cited from Schlick *et al.* 2010, p. 42)

In this context, in addition to the level and duration of the exposure, the characteristics of the worker are of particular importance (Rohmert, 1984). Since the characteristics differ from person to person, an identical exposure leads to individual strain reactions. Thus, in contrast to stress exposure, which can be measured according to its level and duration, the strain of the working person cannot be measured in a generally valid way (Wittemann, 2017, p. 14).

2.2.6.1 Musculoskeletal disorders and their relation to stress and strain

Musculoskeletal disorders are defined by the World Health Organization (WHO) as health problems of the locomotor apparatus (i.e. of muscles, tendons, the skeleton, cartilage, ligaments, and nerves). MSD include all forms of ill-health ranging from light transitory disorders to irreversible and disabling injuries (Luttmann *et al.*, 2003, p. 2). The risk for developing MSD is associated with a combination of personal factors, psychological and psychosocial factors, and physical exposures at work in combination with poor ergonomic working conditions. Factors promoting the development of MSD include physical, psychological, and personal, as well as impact factors from the work environment. (Punnett and Wegman, 2004, p. 14; Institute of Medicine, 2001, pp. 364–365) The risk factors for MSD were studied and described by several authors.[2] Also the magnitude of the biomechanical factors that could cause damage, has been studied.[3] However, there is no consensus about the dose-response relationships and critical exposure times for both, during the working day and in course of working life (Punnett and Wegman, 2017, p. 360).

Based on experimental studies and epidemiologic investigations, frequently cited features that are considered as risk factors for MSD within the personal domain are especially (1) the Body Mass Index (BMI), (2) the gender and (3) the age (Institute of Medicine, 2001, pp. 364–365, pp. 98-99). For the psychological domain evidence for the relationship between MSD and job satisfaction, monotonous work, work relations, high job demands, psychological stress, and the perceived ability to work are available in literature (Institute of Medicine, 2001, pp. 354–355). Within the physical category heavy physical work, non-neutral body postures (either dynamic or static) including awkward body postures, heavy lifting, forceful manual exertions, rapid work pace and repetitive motion patterns, insufficient recovery time, segmental or whole-body vibration, local or whole-body exposure to cold, and any combination of these factors have been proven to promote the risk for MSD development (Punnett and Wegman, 2017, p. 357).

Even if several studies have shown that both, physical and psychologically demanding jobs might lead to MSDs[4], work-related musculoskeletal disorders are however mainly caused by a mechanical overload and supposed to be causally linked to physical load, resulting from occupational activities (Luttmann *et al.*, 2003, p. 3). Previous studies have shown that workers exposed to physical demanding job tasks are at greater risk of reporting MSD, compared to less physically demanding jobs and most MSD are reported for upper limbs and the lower back area (Hartvigsen *et al.*, 2018, Tsai *et al.*, 2011 Gould *et al.*, 2008). In addition, literature indicates that MSD can be developed by usual occupational levels of mechanical loading, that can be expected in most workplaces (Institute of Medicine, 2001, pp. 252–253).

The most common musculoskeletal disorder and thus the leading cause of activity limitation and disability in high-income countries still are MSD in the upper limb area and low back disorders (LBD) (Theo *et al.*, 2017, p. 1211). Literature reviews of associated risk in specific industries present on the one hand that significantly increased risk of MSD in the back is available for occupations that tend to impose greater physical weights on workers, such as order picking in logistics workplaces, warehouses or distribution centers (Institute of Medicine, 2001, pp. 434–435). On the other hand, MSD in the upper limbs particularly in shoulder, elbow or wrist area is related to job profiles determined by repetitive movements, action forces and unfavourable postures, as typically found in assembly workplaces (Benker *et al.*, 2016, p. 22).

2.2.6.2 Task-related factors causing MSD

LBD are causing major health problems, largescale work absenteeism and socioeconomic costs (Wynne-Jones *et al.*, 2014, p. 451,).Lambeek *et al.*, 2011, p. 1057 LBP affects about 60 to 80% of all people at some point in their lifetime (Baltrusch *et al.*, 2018, p. 94). Despite increasing awareness of the need for

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[2] Compare e.g. Kilbom (1999); Kuijer *et al.* (2012); Bernard (1997), Grieco *et al.* (1998); Andersen *et al.* (2007); Punnett (2014), Punnett and Wegman (2004, 2017); Silverstein *et al.* (1997).

[3] Compare e.g. Bernard (1997) Kilbom (1994); Nordander *et al.* (2013).

[4] For an overview of related studies see Varianou-Mikellidou *et al.* (2019, p. 239).

prevention, the prevalence of MSD has not decreased and low-back injuries continue to be a major occupational health problem (Lotz *et al.*, 2009, p. 332). Numerous peer reviewed studies have investigated the main factors associated with risk for low back disorders (LBD).[5] Results show on the one hand, that especially heavy physical work, lifting, the physical load, the frequency of bending and twisting, and whole-body vibration are strongly correlated with LBD development risk. For these factors a relative risk to develop LBP up to the 9-fold compared to workers in the same industries without these factors were reported (Institute of Medicine, 2001, pp. 434–435). Further, different cross-sectional studies showed that a similar association between towing and pushing operations and musculoskeletal disorders exist (Placci *et al.*, 2019, p. 418). On the other hand, evidence for (awkward) static postures and frequent repetitive movements are less compelling. Data from different studies did not indicate a relationship between low back disorders and static posture (Hoozemans *et al.*, 1998, p.775; Institute of Medicine, 2001, pp. 434–435). An exception in static work postures and their contribution to LBP risk exists, considering prolonged standing activities, which result in an increased risk of chronic venous and musculoskeletal diseases as well as lower limb discomfort and pain (Wall, Seibt and Steinhilber 2016, pp. 12; Werner *et al.*, 2010, p. 111; Andersen *et al.*, 2007, p. 1360; Gregory and Callaghan, 2008, p. 86) The development of the latter is mainly the result of stationary standing, and to a lesser extent of dynamic standing (Luger *et al.*, 2019b, p. 152).

2.2.6.3 Age-related analysis of MSD prevalence

The prevalence of MSD also significantly increases with age, consequently challenging sustainable employability among the ageing workforce (Seeberg *et al.*, 2019, p. 2). As a result, the MSD related proportion of sick days steadily increases with increasing average age of employees. While health problems caused by MSD within the general working population overall increase by about 22% between the age of 30 and 64 years in Austria (Leoni and Böheim, 2018, pp. 48–49), the prevalence of musculoskeletal disorders may increase by as much as 15% among workers between the age of 51 to 62 years, with an even more pronounced increase of about up to 25% in physically demanding occupation (Ilmarinen, 2002a, p. 21). In a case study of a production workforce including 13.000 workers, 5% of employees aged up to 40 years showed restrictions that impede further employment at their traditional workplace. This number increased to 45% for 60 year olds. In addition, also the proportion of those who can no longer be employed by the company, due to a lack of adequate jobs is increasing to up to 15%. MSD was identified as the main reason for the restrictions. (Dubian, 2009, pp. 77–78). Similar, the analysis of the age profiles of selected MSD for about 3500 workers conducted by Landau 2012, showed that most diseases occur in the 45 to 54 years of age group (Landau *et al.*, 2012, p. 81). Moreover, MDS is the main cause of incapacity to work among workers in the age group of 50 to 65 years, causing the largest proportion of work absenteeism (Scheller *et al.*, 2015, p. 138), and one major reason for reduced work ability and productivity (Varianou-Mikellidou *et al.*, 2019, p. 239).

In relation to the two types of MSD highlighted beforehand, Snook (1987) analyzed work-related back problems and injuries, concluding an increased prevalence among older workers (Snook, 1987, pp. 241–247). In addition, Qin *et al.* analysed the development of shoulder muscle fatigue during a repetitive manual task, concluding that older adults tend to develop muscle fatigue faster, with a potential higher risk of musculoskeletal symptoms in specific muscles (Qin *et al.*, 2014). Moreover, Landau *et al.* studied long-term cumulative effects on musculoskeletal disorders among older workers noting increased low back problems, upper limb problems as well as head-, neck- and shoulders-symptoms among elderly

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[5] For an overview see Punnett and Wegman (2004, p. 19)

workers, although they were working in jobs with low physical demands (Landau *et al.*, 2008; Landau *et al.*, 2011). Thus, a general increase in MSD in older age independent of the workload could be assumed. However, Oliv *et al.* reported that elderly workers not exposed to physically demanding jobs during their life time occupation, showed less or no back pain symptoms, in contrast to those exposed to high physical demands at work (Oliv *et al.*, 2017, p. 358). This shows that there is no general increase in back pain and MSDs with age alone, but that high physical workload is connected to increased MDS prevalence in higher age. Several other studies also pointed out that in many cases older workers are reallocated to less physical demanding jobs, hence indicating that demanding jobs have to be carried out by younger workers, who, as a result, experience even higher risks of developing MSD (Carrillo-Castrillo *et al.*, 2016, p. 75). In addition, a substantially higher rate of musculoskeletal injury complaints is reported for females, which is considered to be mainly attributable to their lower physical work capacity, muscular strength and endurance in comparison to males (Kenny *et al.*, 2008, p. 617), showing the impact on physical abilities on MSD risk.

2.2.7 Management of MSD risks

In short, it can be summarized that there is a strong biomechanical evidence concerning the relationship between the risk of developing MSD and the exposure to physical loading in the workplace. MSD risk is mostly associated with high physically demanding jobs, including in particular heavy physical work, and work activities of lifting pushing and pulling of heavy goods, and prolonged standing. Further, MSD risk is significantly increased in relation to high physical demanding jobs for workers with on average lower physical prerequisites which particularly affects the female workforce. These overstraining job tasks as promoter of developing MSD present an increased problem for elderly workerswho are exposed to a health risk due to the accumulation of the duration of exposure of multiple exposure. It is therefore necessary to examine and adapt the stress to which employees of different ages are exposed (Ilmarinen, 2001). Hence, companies with high proportion of manual handling activities, must expect an increase in related problems and work absenteeism (Liebers *et al.*, 2013).

To reduce work-related injuries, illnesses and MSD, in general a proper match between the worker and the job is recommended (Snook, 1987, pp. 241–247). It is evident that the appropriate reduction of exposure to physically overstraining work can decrease the risk of MSD in general and specifically for LBD. Hence, to reduce the risk, it is of great importance that job demands are in balance with workers abilities (Snook, 1987, pp. 241–247, Institute of Medicine, 2001, pp. 252–253). Thus, the optimal solution would be the individual assessment of the relevant skills for specific workers. Scientific literature provides Functional Capacity Evaluation (FCE) tests which are used to assess the work-related performance and to classify changes in performance. Depending on the purpose of the test, various physical or psychosocial factors are assessed. (Schian *et al.*, 2004, pp. 264–271) In terms of psychological factors, the approach of aptitude diagnostics can be used which builds on a requirements analysis of the activities needed. The job requirements are determined using a standardized, analytical procedure. These procedures often follow an atomistic approach and divide the job into different psycho-physical requirements. However, many of these psychodiagnostic procedures for determining the suitability of applicants are, methodologically doubtful and their prognostic validity is usually unclear (Bokranz and Landau, 2012, pp. 254–255). For physical factors the American Physical Therapy Association (APTA) published guidelines for the evaluation of functional capacity, naming 17 functional activities based on the Dictionary of Occupational Titles (DOT, 1991) that should be included in an FCE analysis (APTA, 2011). These activities include the abilities balancing, carrying, climbing, crawling, crouching, feeling, fingering, handling, kneeling, lifting, pulling, pushing, reaching, sitting, standing, stooping and walking (Schian *et al.*, 2004), as shown in Table 2.

Table 2: Content of FCE tests (Schian *et al.*, 2004)

Dictionary of Occupational Titles	
Strength for:	Handling
Body posture: Standing, walking, sitting	Fingering
Weight and force: Lifting carrying pushing, pulling	Feeling
Controls: hand-arm and foot-leg	Talking
Climbing	Hearing
Balancing	Tasting / smelling
Stooping	Near and far acuity
Kneeling	Depth perception and accommodation
Crawling	Colour vision
Reaching	Field of vision

In operational practice capabilities of workers are mostly assessed by a rating of occupational physicians after a medical examination, but there is no standard procedure in use. Several FCE assessment methods are available like the Ergos Work Simulator, the Valpar Component Work Samples (VCWS), the Arcon FCE System and the Bavarian Rehabilitation Assessment (BRA) (Schian *et al.*, 2004, pp. 264–271). The items assessed can differ between different methods (Müglich *et al.*, 2015a, p. 2).

A very common method in the field of FCE testing is the assessment by Isernhagen, which was developed for the assessment of work-ability of rehabilitation patients (cf. Kaiser *et al.*, 2000). This test include the assessment of force related and 17 body posture and movement related abilities in 20 standardized tests, as well as the assessment of pain symptoms and a self-assessment of the worker in relation to several tasks (Performance assessment capacity testing PACT). The conduction of the tests takes about 6 hours divided in a two-day test procedure. (Kaiser *et al.*, 2000, pp. 298–301, Rademacher *et al.*, 2013, p. 233) A similar EFL test, the ERGOS work simulation evaluates the performance based on 240 tasks in order to derive qualitative and quantitative statements on the resilience of an employee. The tests comprise five examination stations for lifting, pushing and pulling, whole-body mobility, work endurance and workload in standing, walking and sitting, at which 42 individual tasks are evaluated (Egbers, 2013, p. 39). The EFL assessment includes 29 test and usually takes about two days to be completed. The BRA includes 110 items including educational, social, physical and organizational aspects and a medical assessment (Landau *et al.*, 2007a, p. 71). To shorten test durations, Rademacher et al. 2009 developed a three-hour assessment which consists of a medical examination, interview with several questionnaires and a test procedure with numerous work-specific trials for to assembly work. The testing procedure is a good approach for a work-related assessment, but is difficult to include the complete assessment into a daily routine of occupational physicians. Müglich *et al.* suggested an even shorter procedure including a medical examination, functional tests and a questionnaire adapted to the need of occupational physicians working in the manufacturing industry. The test procedure for these capabilities consists of two stages whereas either capability tests and individual abilities or rules based on models of disorders can be used. The capability levels are classified roughly into the four expansions of no (1), light (2), medium (3), and severe (4) limitation. (Müglich *et al.*, 2015a, 3-6) However, the different methods have in common that they are not practical for occupational practice in industry, because they are too complex, too time consuming and too expensive (Müglich *et al.*, 2015a, p. 2). Therefore, in practice, it is above all the age of workers that influences the choice of workplace and thus the experienced exposure to stress. Older workers are preferred in workplaces that are considered to provide low stress levels. (Landau *et al.*, 2008, p. 569; Egbers, 2013, pp. 17–18). Considering the numbers of sick related absence, this practice is reaching its limits, thus instead of the individual assessment of particular abilities, general changes in human abilities can be a suitable improvement regarding strain based work design (cf. Keil, 2011)

A classification of main relevant skills for manufacturing and logistics industry can be derived in accordance to the dictionary of occupational titles (DOT) and models of Tittor *et al.*, 2004 and Müglich *et* *al.*, 2015a. Figure 12 shows an overview of different skills relevant for physical work as available in industry. According to these models the most important physical capabilities in these industries can be broken down into the categories of manual material handling, locomotion, body postures, action forces and use of upper limbs (Müglich *et al.*, 2015a, 3).

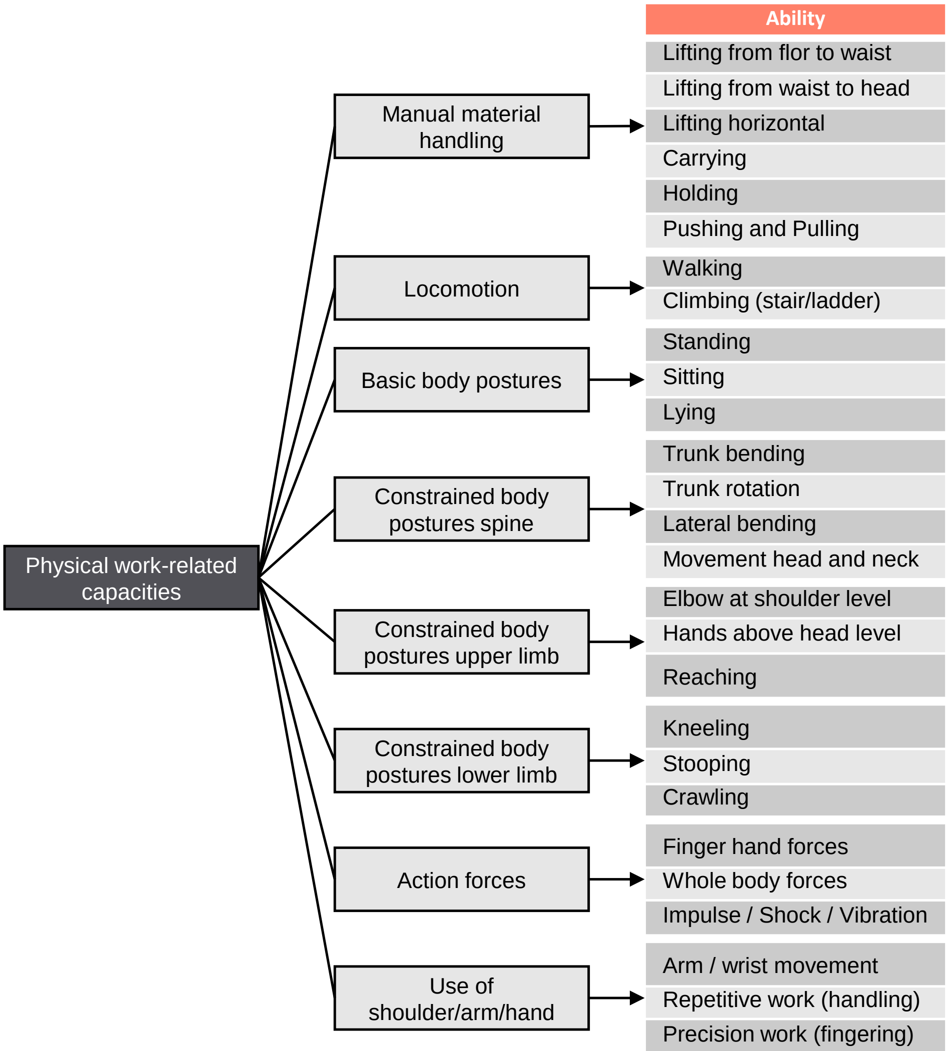


Figure 12: Main abilities relevant for manufacturing and logistics workplaces (own representation, model based on Tittor *et al.*, 2004, p. 212, Müglich *et al.*, 2015a, 3)

In conclusion, every type of industrial work implies hazards and health risk for the worker. In relation to the demographic challenges, especially physical work that causes physical stress were identified to be a major problem. In particular, physical overload or overstrain in manual material handling is strongly related to the risk of develoing MSD, which are a major burden for the elderly workers. It follows that the risk only can be identified and managed when the loading is evaluated in relation to physical worker prerequisites (Institute of Medicine, 2001, pp. 252–253). Acc0rding to the stress-strain concept overstrain is the result if physical requirements at the workplace are not met by the ability levels of the workers. Therefore, the next section deals with the age-related changes of physical abilities with increasing age.

2.3 AGEING-RELATED CHANGES OF HUMAN ABILITIES

In this section the effects of ageing on human abilities are summarized. Based on literature a comprehensive overview of abilities that change during ageing is provided. Emphasis is first put on workability and positive changes, as well as compensation strategies. Then physical decline of the cardiopulmonary system, the musculoskeletal system, the sensory system, and cognitive skills and abilities are described.

2.3.1 Overview of age-related changes.

The term age is often used in a variety of ways, referring to the definitions of chronological, biological, functional and social age (Landau *et al.*, 2012, p. 78). The chronological age is a temporal measure of the duration of the existence of a person and is often used to define the term older workers. Biological age refers to the physiological and anatomical changes associated with a certain age. Such biologically developments cannot be precisely assigned to a particular chronological age, since there are individual differences in the ageing process. Individual differences are considered in the functional age definition, which is based on a performance-oriented view and can be determined by the state of health, physical and cognitive performance prerequisites or the work performance. (Bruggmann, 2000, pp. 6–9). Finally, social age is based on the perception of a person by the society (Landau *et al.*, 2007b, p. 78). For this thesis a combination of the chronological and functional age definition is applicable.

A scientific model to cluster age-related changes in relation to work design was introduced by Keil, 2011. In this model, human work is divided in information perception, processing, and execution and the related human abilities are named as vision, hearing, sense of touch, intelligence, physical strength and endurance, coordination and body structure and flexibility (Keil, 2011, p. 45). Based on the stress-strain model changes in these abilities influence the perceived strain at the workplace, if work system design is not adapted. In order to determine weather and to what extend skill limits are exceeded by the job requirements, the broad categories of age-related skills defined in the model, have to be further differentiated. Every skill category consists of a number of age-related performance factors, where each can increase or decrease the overall performance depending on age. Therefore, clear suggestions for work design can only be based on the comparison of specific performance factors with relevant work requirements (Keil, 2011, pp. 47–49).

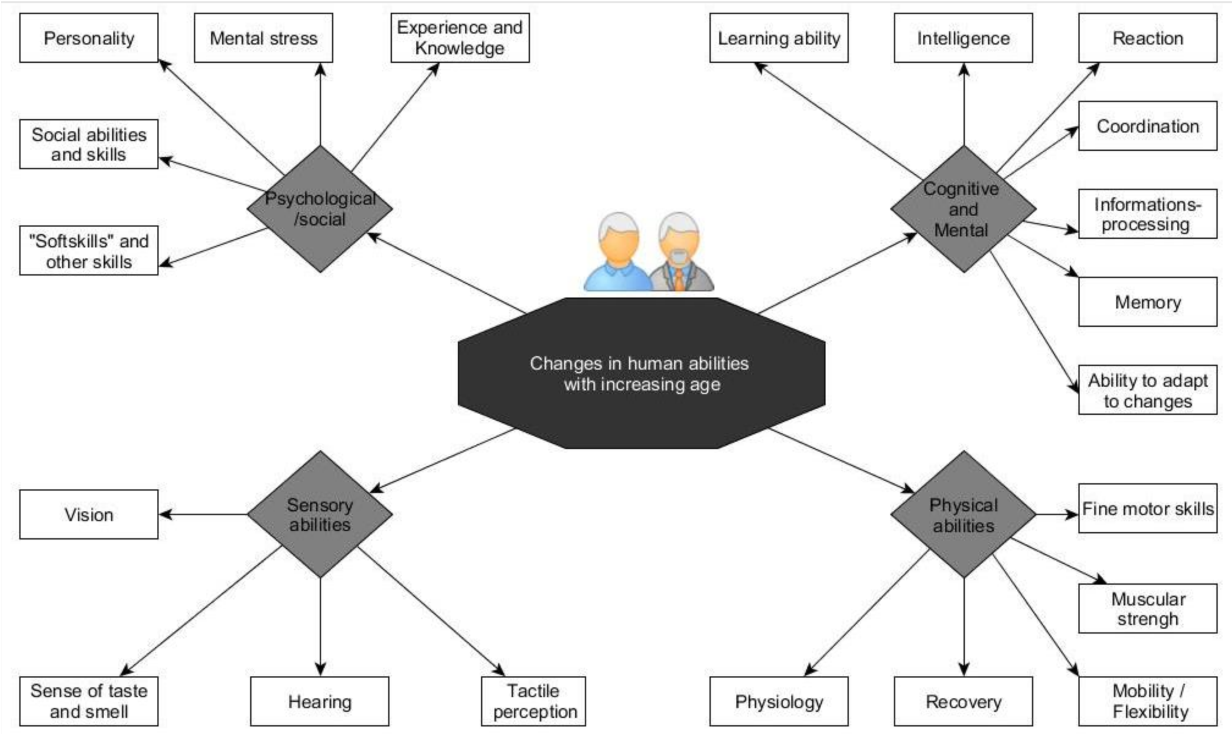


Figure 13: Areas of change in human abilities with age [based on (Wolf *et al.*, 2018, p. 71; Wolf, 2015, p. 47)]

Capabilities in ergonomics are defined as the potential to perform an action or to produce a physical or mental work outcome (WIAD, 2013), and can be differentiated in mental, physical, sensory, and social capabilities (Tittor *et al.*, 2004). To enable a detail comparison, an overview of general tendencies of age-related changes in human abilities on performance factor level was conducted by in the pre-study by the author of this thesis (Wolf, 2015). The results are illustrated in Figure 13. In total, four groups of relevant skills with 22 sub-groups were identified and assessed including physical, cognitive and mental, psychological and social as well as sensory skills. It was concluded that sensory and physical abilities generally decline with age, whereas psychological and social skill on average increase. Further, the cognitive-mental skills show different changes with increasing age. While some abilities decline, others increase or remain at the same level, so that no general trend can be identified within this category. In extension to the model by Keil the category of social skills, as an asset of elderly workers, was added. (Wolf, 2015, p. 47). Overall 96 performance factors were gathered on specific ability level and average age-related changes of these abilities was documented (Kleindienst *et al.*, 2015).

Figure 14 shows a summary of the results on performance factored level. The direction of the triangle indicators shows the general trend in age induced changes (up-increase, down-decrease). White triangles indicate a positive development or improvement of skills, while black triangles indicate a deterioration or a negative trend. Grey arrows symbolize a change in the abilities, but there is no clear positive or negative tendency.

Physical abilities	Fine motor skills	Coordination ability	▼	Palpation of details	▼	Tendency to tremble	▲	Dexterity	▼		
	Physical Strength	Muscle power	▼	Muscle endurance	▼	Muscle impulse force	▼				
	Mobility	Mobility of the joint system	▼	Speed of movements	▼	Rheumatic diseases	▲	Bending- and stretching	▼	Deformation of the intervertebral discs	▲
		Elasticity of the spine	▼	Strength of joints	▼						
	Physiological functionality	Oxygen absorption - continuous output	▼	Performance of the immune system	▼	Performance of the hormonal system	▼	Performance of the cardiovascular system	▼		
	Recreation	Energy reserves and functional capacity	▼	Perceived strain	▲	Regeneration period	▲				
Sensoryabilities	Vision	Visual acuity	▼	Color perception	▼	Depth perception	▼	Contrast sensitivity	▼	Size of the visual field	▼
		Presbyopia	▲	Lighting requirements (geriatric osmosis)	▲	Dark adjustment of the eye	▼	Focusing speed of the eye	▼	Light transmission	▼
		Glare sensitivity	▲								
	Smell and taste	Olfactory performance	▼	Sense of taste	▼						
	Hearing	Perception of volume changes	▼	Perception of frequency changes	▼	Age-related hearing loss at high frequencies	▲	Hearing and distinguishing soft consonants	▼	Filtering background noise	▼
	Sense of touching	Tactile efficiency	▼	Vibration sensitivity	▼	Sensitivity to pain	▲	Manual differentiation	▼		
Psychosocial skills	Experience and knowledge	Practice and Experience	△	Special operational knowledge	△	Life and work experience	△	General knowledge	⬌		
	Stress	Stress perception	▲	Stress resistance	⬌	Stress management	⬌				
	Personality	Ambition	▽	Risk appetite	▽	Critical thinking	△	Extraversion	▽	Loyalty	△
		Time flexibility	△	Tolerability	△	Conscientiousness	△	Openness to experience	▼	Ability to concentrate	⬌
	Adaptability	Self-assessment ability	△	Balance and serenity	△	Emotional consistency and stability	△	Willingness to adapt Flexibility of mind	▼	Fear of change	▲
Cognitive and mental abilities	Social skills	Ability to communicate	△	Language competence / Expressiveness	△	Conflict management skills	△	Ability to work in a team	▽		
	"Soft skills"	Creativity	▼	Leadership abilities	△	Awareness of quality and responsibility	△	Assessment ability in complex situations	△	Decision-making ability	△
	Learning	Willingness to learn	▼	Speed of learning	▼	Learning ability	▼				
	Intelligence and memory	Crystalline Intelligence	△	Fluid Intelligence	▼	Short-term memory	▼	Speed of decoding and encoding of information	▼	Long-term memory and retentiveness	⬌
	Reaction	Reaction speed	▼	Comprehension speed	▼	Performance speed for complex activities	▼	Decision speed	△	Frightfulness (second of fright)	▲
		Execution speed for action chains	▼	Susceptibility to sensory overload	▲						
	Information processing	Search for and availability of stored memory content	▼	Linking and memorizing new information	▼	Quantity of information that can be processed simultaneously	▼	Recording, processing, searching and thinking speed	▼	Overall capacity of recording and processing	⬌
	Coordination	Responsiveness	▼	Liquid cognitive skills	▼	Fine motor skills with movement	▼	Information processing speed	▼	Coordinative memory performance	▼

Figure 14: Trends of change in performance factors with age (Kleindienst *et al.*, 2015, p. 182; Wolf, 2015, p. 47)]

As shown in Figure 14 a multitude of performance factors change while ageing. Not all of them interfere with work to the same amount. In the following section some skills that are an important prerequisite for work and their influences on the work ability are described more in detail.

2.3.1.1 Age-related changes in the working capacity

The work ability is made up of various factors and is defined as the ability of a person to perform a service over a longer period of time without suffering heath damages. According to Ilmarinen, the individual work ability is related to individual human resources which are a combination of health status, functional capacity (physical, mental, social), education and competence related factors and motivation related factors including values and attitudes (Ilmarinen, 2001, p. 548). Therefore, the work ability looks at an individual's resources in relation to the demands of the work (EUOSH, 2016b, pp. 46–48). General trends in how the individual resources i.e. abilities and skills change during the ageing process are described in the compensation model of ageing, where it is assumed that different skills, can either decrease, remain constant or increase (Lehr, 2007, p. 65)

While different abilities decline, elderly workers often apply compensatory strategies that rely on increasing skills so that their overall performance remains constant or is influenced positively (EUOSH, 2009, p. 30). Thus a large individual variability in the workability can exist between people of the same age (Biermann and Weißmantel, 1997, p. 161; Riedel *et al.*, 2012, p. 14; Kawakami *et al.*, 1999, 527).

When considering the overall ability to work, it was found that the inter-individual variability (i.e. variation between different individuals of the same age) is higher in the group of elderly workers compared to the variability between younger and older persons (EUOSH, 2009, p. 30). Further, training and healthy lifestyles can mitigate or positively influence many of these declining changes (Kenny *et al.*, 2008; Hamberg van-Reenen *et al.*, 2009).

Nevertheless literature also states that the general decline in physical processes and abilities cannot be totally compensated by any available means (Kawakami *et al.*, 1999; Jungmann *et al.*, 2016, pp. 69–70; Zülch, 2010, p. 401). Even for master level athletes a statistically significant decline of the physical performance with increasing age has been shown (Kenny *et al.*, 2008, p. 612), proving that training cannot totally compensate for age-related changes. Enforcing that argument, Shephard showed that eight of nine abilities strongly and causally related to job performance were found to decline with age (Shephard, 2000, p. 536).

In order to understand the changes in human performance, some important physical changes that may have an impact on the workplace will be explained. Personal factors as well as external circumstances can be identified as factors that influence performance (Jaeger, 2015a, p. 28). First of all, it should be stated that the changes while ageing described below are fundamental trends that apply to the untrained ageing person in general. Inter-individual differences as explained above will cause that not every trend is applicable for every person, but the general average changes of human abilities with age can be derived from literature as follows.

2.3.1.2 Physiological and physical changes

The human body is generally subject to a multitude of age-related physiological changes. With "normal" aging, a decrease in physical performance can be observed with increasing age, although it is often not sufficiently clarified if this decrease is primarily age-related or whether caused by pathological changes (Riedel et al. 2012, p.17). Age-related causes for the impairment of physical performance can be structural changes of the body and associated functional changes of abilities (Biermann and Weißmantel, 1997, p. 161). Age-related physiological changes can be identified in every complex system of the human body, such as the central nervous system, the cardiovascular system and the psychomotor system, as well as the hormone system, the digestive system and the immune system (Rensing and Rippe, 2014, pp 107, pp 226; Riedel *et al.*, 2012, p. 14).

Age-dependent changes of these systems are described in detail in Riedel et al. 2012. Age-typical changes in the cardiovascular system are mainly caused by changes in the lungs, which can result in reduced breathing volume, lower oxygen uptake and thus lower energy supply and physical performance after the age of 20 years (Rinnerhofer, 2012, p. 8ff). At the same time, the maximum possible heart rate decreases as a function of age, which reduces the maximum capacity of the organism and the ability for thermoregulation (Rinnerhofer, 2012, pp. 31–32). The hormone system is influenced by changes in the concentration of hormones and signal substances as well as their effect. Some hormones have a reduced effect, others a significantly increased effect. Especially the stress hormone system loses its effectiveness (Rensing and Rippe, 2014, p. 211). Due to a worse skin barrier due to changes in the skin, as well as a reduction in some immune cells, the defensive performance of the human body decreases with increasing age. Also the efficiency of the existing immune cells decreases with advancing age. In addition, there is an increased production of certain substances which can promote the tendency to inflammation and the development of chronic inflammations. This significantly increases the susceptibility to infections, the formation of tumours and autoimmune diseases, which can lead to an increase in absenteeism due to illness (Rensing and Rippe, 2014, p. 156; Jaeger, 2015b, p. 47). The decrease in maximum capacity and some functions associated with the cardiovascular system such as oxygen uptake, vital capacity and cardiac output are shown in Figure 15.

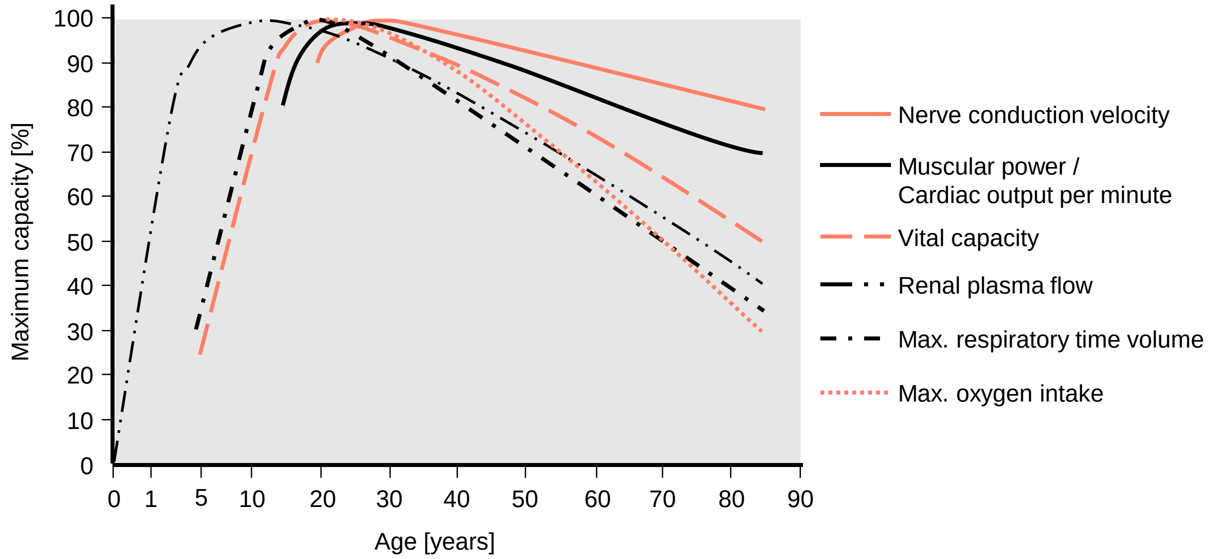


Figure 15: Age-related changes of different vital parameters [adapted from (Zeyfang *et al.*, 2013, p. 65)]

The physiological changes generally lead to a deterioration in the body's resistance to external influences and stress. Further, the maximal physical capacity to work declines with increasing age, which is of importance in physically demanding occupations like the metal industry (Kang *et al.*, 2007).

Recovery

Due to the slower processes in the body, the time needed for regeneration after stress increases (Riedel *et al.*, 2012, p. 96). A further increase in the recovery period is caused by the fact that older people often have to perform closely to their performance limit in order to cope with their tasks, and thus there is a greater need for recovery. At the same time, they are also less able to switch between stress and recovery, which can lead to an increase in work-related overstrain (Ilmarinen, 2006b, p. 172).

Another important term in this context is chronobiology, which deals with the temporal course of biological functions and their periodic behaviour. Human activities and biological processes are subject to the so-called circadian rhythm, a 24-hour period. The circadian rhythm regulates the "inner clock" of the human and thus controls the sleep and activity behaviour which is regulated by external timers, especially daylight (Rensing and Rippe, 2014, p. 238; Ilmarinen *et al.*, 2002b, p. 258). Human performance is also subject to this circadian rhythm. With advancing age this sleep-wake rhythm of humans changes, whereby the nightly sleep phases decrease, tiredness and thus the need for short recovery phases increase over the day and the sleep time shifts to earlier hours (Münch *et al.*, 2005, 22), which is to be led back to a shortening of the period length (approx. 30% decrease in the age over 60 years). At the same time, the amplitude of the circadian rhythm also decreases, which is accompanied by a more frequent alternation of activity phases and rest phases (approx. every 3-4h) (Hecht, 2001, p. 340). The changes in the internal rhythm also effect other functions such as body temperature, hormone release, heart rate and blood pressure, as well as subjective alertness and performance and their daily course (Rensing and Rippe, 2014, p. 238). In older workers, these changes often reduce the ability to work at full capacity in normal working time models, such as shift work.

Physical strength

By reducing the oxygen uptake and oxygen conduction in the body, as well as by changing the hormone and mineral balance, a decrease in the muscle fibres of the skeletal muscles, and the quality of these muscles reduces the muscle force and physical strength of a person with advancing age (Riedel *et al.*, 2012, p. 20; Rensing and Rippe, 2014, pp. 89–91; Biermann and Weißmantel, 1997, p. 173). All muscle related abilities, namely muscle maximum strength, muscle endurance and muscle impulse strength are constantly decreasing (Lang & Arnold 1991, p.101). For example, the repetitive application of (small) forces can be difficult for older people, especially if the moving objects are small or smooth (Biermann and Weißmantel, 1997, p. 173). Even if the amount of task where muscular force is needed in production is decreasing, due to the increasing mechanization of work processes, several occupations and tasks remain where muscular strength is a prerequisite for preforming the work. Therefore, the higher strain on older people with the same force load must be taken into account. The results for work design can be illustrated with a study conducted by Chen et al. in 2017, who studied the effects of age on estimates of maximum acceptable lifting loads. Their results showed that older workers selected their maximum acceptable lift weight on average 24% lower than those picked by younger workers (Chen *et al.*, 2017).

Mobility

The mobility of a person at an advanced age decreases caused by a decrease of the water content in the body, decreasing of the skeletal muscle mass, an increasing probability of pain due to pathological changes and rheumatic diseases, as well as decreasing bone mass, bone and cartilage strength, a deterioration of the joints as well as by changes in shape and elasticity of the spine and intervertebral discs (Biermann and Weißmantel, 1997, p. 172; Rensing and Rippe, 2014, pp. 72–74).

Due to the limited ability to bend, as well as difficulties and pain when taking up forced positions (e.g. kneeling, bending, etc.), the range of motion of older people is increasingly restricted. Especially, to reach objects above head height or on the ground becomes an increasing strain, or may become an impossible task (Biermann and Weißmantel, 1997, p. 172). In addition, the reduced muscle impulse force and reduced sensory speed and nerve conduction speed also reduces the speed of movement (Rensing and Rippe, 2014, p. 232). The significance of reduced mobility for work was shown by Chung and Wang (2009), who highlighted in a study how different age groups tend to have different capabilities in joint mobility, with an age induced decline. Problems were identified particularly in the cervical spine and the wrist joint (Chung and Wang, 2009). Therefor a decreasing mobility of the working persons results in increased demands on the workstation design and work environment design.

Dexterity

When performing fine motor actions that require dexterity, the reduction of sensory and motor skills during aging often results in significant losses in fine motor skills (Riedel *et al.*, 2012, p. 14). In addition, negative effects on muscle endurance, which can lead to faster muscle fatigue and associated muscle tremor, making fine motor actions more difficult. Decreasing mobility, reduced sense of touch and limited coordination ability due to sensory systems (Biermann and Weißmantel, 1997, p. 175), as well as a fundamental slowing down of mental processes and movements can further impair finger dexterity negatively (Rensing and Rippe, 2014, p. 232). In addition, an increased reduction in the abilities of the dominant hand, as well as a fundamental decrease in the accuracy of movements and coordination can be identified as age-related changes of dexterity skills (Kalisch et al 2006 and Desai et al 2005 cited from Riedel *et al.*, 2012, p. 22). Decreasing dexterity skills with age as shown by (Pennathur *et al.*, 2003) at industrial workplaces, e.g. in assembly, can lead to a greatly increased strain on the workers as shown by Qin *et al*. who analysed the development of shoulder muscle fatigue during a repetitive manual task. Older adults tended to develop muscle fatigue faster, with a potential higher risk of musculoskeletal symptoms in the affected muscles (Qin *et al.*, 2014).

2.3.1.3 Changes in the sensory system

The human sensory system is formed by the sensory organs and their functions. By means of hearing, seeing, touching, smelling and tasting, all information of the environment is incorporated. Numerous physiological changes cause all these functions to deteriorate in older age and thus influence human performance. An overview of the changes in sensory abilities in old age can be seen in Figure 16. Here the average age of the start of such changes is indicated by an age number and the arrows indicate the progressive development of the decline. For detailed information see (Biermann and Weißmantel, 1997; Rensing and Rippe, 2014; Wolf, 2015).

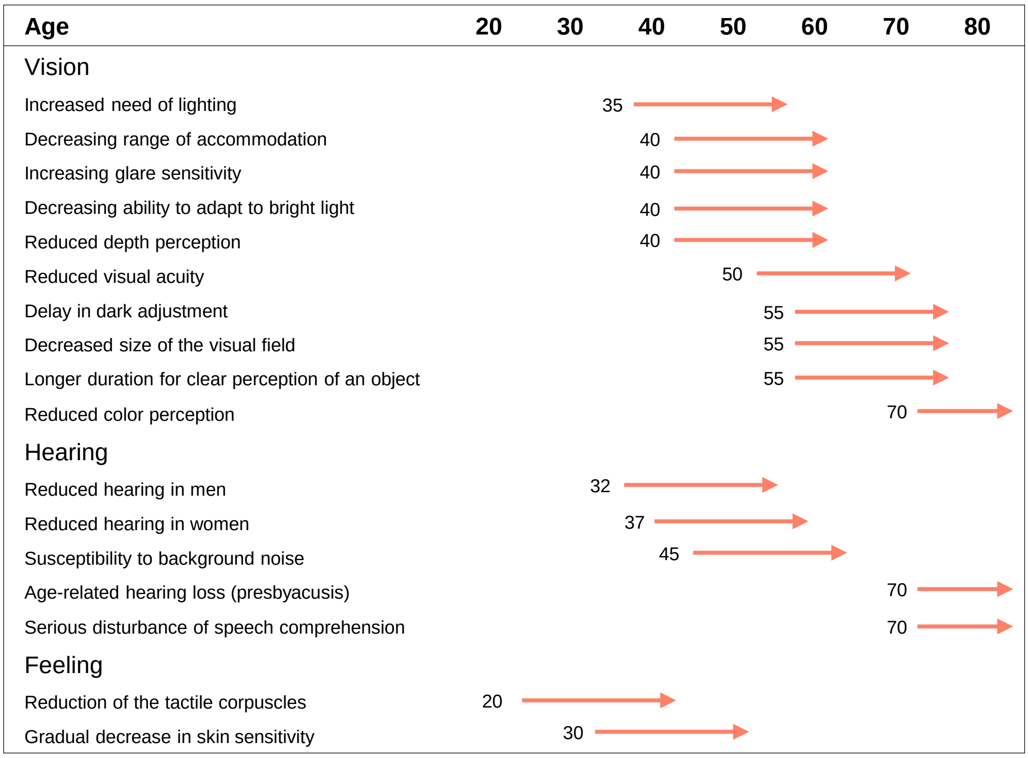


Figure 16: Age-related changes of sensory abilities (cf. (Saup, 1993, p. 76)

2.3.1.4 Changes increasing the performance of elderly workers

While physical skills are significantly decreasing with age, changes in cognitive skills and psychosocial characteristics are often responsible for a performance increase of elderly workers. Since ageing is a highly individual process, it is difficult to define general tendencies for such characteristics and related changes in higher age. However, general positive tendencies are outlined in this section, while other related changes can be retrieved from related literature (cf. Wolf, 2015).

Especially occupational experience accumulating over the course of life can lead to an increased overall intelligence in older age due to the compensation of physical deficits by knowledge and experience (Schlick *et al.*, 2010, p. 126; Bruggmann, 2000, p. 25; Ilmarinen, 2006b, p. 202; Kruse, 2000, p. 75). Vigilance or long-term attention can be regarded as tending to be constant with age (Prasch, 2010, p. 33). Furthermore, fewer work-related accidents among older people indicate increasing calmness and prudence (Holz and Da-Cruz, 2007, p. 45). Also several “soft skills” as increasing quality awareness, better decision-making, increasing communication, language and expression skills, better conflict resolution skills, higher willingness to cooperate and the ability to work in a team are often described as increasing with age associated with increasing experience (Kruse, 2000, pp. 74–76). This also positively effects leadership skills (Bruggmann, 2000, p. 25; Jaeger, 2015b, p. 43) In relation to positive personality emotional stability, conscientiousness and tolerance increase with age, while openness to experience and extraversion decrease (Srivastava et al. 2003 cited in Schlick *et al.*, 2010, p. 116). Self-esteem, loyalty to the company and critical thinking are increasingly attributed to elderly workers, while ambition and willingness to take risks are also regarded as decreasing factors (Bruggmann, 2000, p. 25; Jaeger, 2015b, p. 43). Moreover, studies revealed that main stressors for older workers were identified as working at the performance limit and constantly recurring work processes, as well as disturbance of the circadian rhythm associated with shift work (Hecht, 2001, p. 338; Lohmann-Haislah and Schütte, 2013, p. 38). However, literature states that the individually perceived feeling of stress is steadily increasing with age (Lohmann-Haislah and Schütte, 2013, p. 85). But also stress coping strategies differ with age. Older people try to avoid stress preventively and prefer strategically planned and problem-related stress management, relying on problem-solving skills, critical and strategic thinking, and a holistic understanding of complex situations (Ritz and Thom, 2011, pp. 45–47).

As all these changes described are of general nature and often measured isolated from work requirements in laboratory settings the provided information for work place design is limited. Based on the multitude of abilities affected by ageing, two important factors to consider are the relevance of different skills for industrial work (1), and the magnitude of ability changes imposed by ageing (2). To clarify these factors, studies examining workers in their natural work setting have to be conducted (Bruder, 2013b). Consequently, the next section summarizes relevant studies in direct relation to industrial work.

2.3.2 Case examples assessing work specific human abilities and problems of elderly workers in industrial work

Several studies assessed the development of human abilities considering the age of the workforce in relation to work requirements in different industries. This is important to identify industry relevant abilities and their related changes. In the following section, studies which compared work related activities with a special focus on elderly workers in industrial work are summarized, focusing first on defining relevant abilities based on problems of elderly workers in industry and second on quantifying associated ability changes.

2.3.2.1 Studies assessing challenges for elderly workers

This section summarizes findings of different studies in relation to problems of elderly workers in industrial work. Besides the body of literature already mentioned in relation to MSD, main challenges can exist in relation to environmental influences, overall workload and related strain and specific physical abilities.

Overall workload and strain

For the automotive industry a study conducted by Rademacher *et al.* clearly demonstrate the absence of age-related factors significantly influencing light to moderate sensomotoric performance in manufacturing. Consequently, there is no urgent need for job redesign in this area (Landau *et al.*, 2012, p. 82). On the other hand, the study concludes that measures to improve job design and reorganize work procedures, especially in load handling procedures need to be taken (Landau *et al.*, 2012, p. 82), relatively independent from physical load level (Rademacher *et al.*, 2013, p. 240).

In a study Egbers analysed the electronics- and metal industry. Within this study ability limitations considering static body postures and bending, material handling and sitting were the major issue in the electronics industry. The share of employees with ability limitations in the total workforce only accounted for 5%, but was strongly age-dependent. the group of employees under 51 years of age low percentages of up to 5% were reported, while in the over-50 age group already 13% were noted (Egbers, 2013, p. 19). Summarized over age groups 16% of the ability limitations were attributable to the group of younger workers (20-45 years). In contrast the amount of limitations in the older group (46-65 years) accounted for 84% (cf. Egbers, 2013, p. 19). For the metal industry the proportion of ability limitations also showed a strong correlation with workers age. Summarized, younger workers (20-45 years) in total accounted for 17% of ability limitations, the older group (46-65 years) for 83% (cf. Egbers, 2013, p. 21). For both studies physical ability restrictions account for the largest share of limitations, thus measures for the physical load are needed (Egbers, 2013, p. 22). The general lower capacity of workers in the metal industry was also confirmed by (Kang *et al.*, 2007)

For logistics work a study conducted by Walch in 2012 also supports the results of aforementioned studies. In this study the four groups of limitations with the highest frequency of occurrence were lifting and carrying, body postures, and basic body movements. These four categories accounted for a relative share of 63% of over 13.000 evaluated profiles. The author concluded that the distribution of the number of restrictions among the defined age groups increases exponentially with increasing workers age (Walch, 2011, pp. 60–61). Especially limitations in the categories lifting and carrying and flexibility of the trunk grow disproportionately strong with age. (Walch, 2011, p. 62). It was concluded that out of all skills that are relevant for operational logistics, physical abilities decline the strongest and that the physical resilience in connection with an ageing workforce must be given priority (Walch, 2011, p. 71). Further, due the low number of limitations in terms of cognitive and mental performance identified in the company's medical data and according to the perspective of the logistics managers surveyed, mental stress generally plays a subordinate role for both young and old workers in logistics (Walch, 2011, p. 70).

A study by Aittomäki *et al.* investigated the interaction of workload, age and gender among Finnish employees and found a linear trend towards less stressful work among older age groups. For work with high physical stress, a correlation between increasing age and lower performance was found. However, a transfer of the results to assembly work in industry, for example, is only permitted to a limited extent due to the group of people analysed (Aittomäki *et al.*, 2005).

Aunola *et al.*, 1978, 1979 and Börner, 2019 investigated the effects of age on strain at constant workloads in machine, manufacturing and automotive industries was analysed. Concluding a significant relation of objectively measured physiological strain, in relation with increasing age. It was concluded that the correlations are highly significant, so that there is at least a medium to strong correlation between age and relative heart rate (Börner, 2019, p. 102).

In 2009 Devereux and Rydstedt conducted a longitudinal survey of over 2090 employees with the aim to identify age effects on recovery times. They concluded that the need for recovery was associated with long working hours, high psychological demands and physically demanding work and that need for recovery was greater in the oldest age group (50–69 years) compared to the youngest group (17–29) (Devereux and Rydstedt, 2009). Similar Kiss *et al.* concluded from a cross-sectional questionnaire survey including 1100 workers that the need for recovery from psychosocial and physical work strain increases with age (Kiss *et al.*, 2008). Also psychophysical scaling for discomfort (King 2002) and maximum acceptable lifting load (Chen *et al.*, 2017) were influenced by workers age.

Environmental influences

In relation to the work environment studies suggest little influence of age on related problems. Pandolf conducted literature reviews on heat intolerance in older individuals stating that age is not a primary factor for heat tolerance. Rather age-related cardiovascular changes and ill-health impact on the individual's heat tolerance (Pandolf, 1997). However, in contrast (Marszalek, 2000) reported a potential greater risk of dehydration among older employees in hot environments and (Thetkathuek *et al.*, 2015) showed increased risk in cold environments. Also an interaction of noise exposure on workers' fatigue in shift work with age was reported (Saremi *et al.*, 2008).

Specific tasks and abilities

Frieling *et al.*, after evaluating a longitudinal study of various assembly activities in the automotive industry, identify a number of characteristics that prove problematic for workers in general and older workers in particular: These characteristics were summarized as high physical stress, short cycle times with a high degree of capacity utilisation (e.g. B. 97%), lack of opportunities for spontaneous work interruptions and breaks, incomplete (group) tasks, high degree of standardisation, insufficient room for manoeuvre and decision-making as well as limited opportunities for participation and development (Frieling *et al.*, 2012).

However, Xu *et al.* investigated the movement time for simulated assembly activities under laboratory conditions. When carrying out work tests with 20 participants, it was found that the older group from 55 to 65 years of age, as well as the younger group from 18 to 28 years of age were able to adhere to the specified times. As a possible explanation for the results, it was cited that the older study participants acted closer to their physical performance limits to compensate for age effects on exercise time. No statement is made about the additional reserves of the respective age group for faster processing of the task (Xu *et al.*, 2014).

Rademacher *et al.* conducted a study where age dependent activity characteristics within the vehicle manufacturing sector were identified by comparing work relevant abilities of younger and older workers of a German car manufacturer. This study showed that different abilities including static or bended body postures, and the ability to lift weights starting from 5 kg show a statistical significant difference between healthy workers within the age groups of 20-35 year olds and 45-63 year olds (Rademacher 2011, cited from Scheller *et al.*, 2015, p. 139).

Wittemann showed similar results for workers with ability limitations or health impairments. For this study 1233 ability profiles of workers with operational restrictions from a German car manufacturer were assessed to identify workplaces were ability limited workers can remain productive. Considering this specific group of workers even more abilities were shown to have a statistical significant difference in comparing younger and older workers. Of a total of 14 assessed abilities in maintaining different body postures 12 showed a significant decline with age (Scheller *et al.*, 2015, p. 142; Wittemann, 2017, p. 45), also all 8 abilities considered within the category “action forces / body part movements” showed significant lower mean values (Wittemann, 2017, p. 48), as well as 9 out of 10 abilities in the category “manual material handling” (Wittemann, 2017, p. 50).

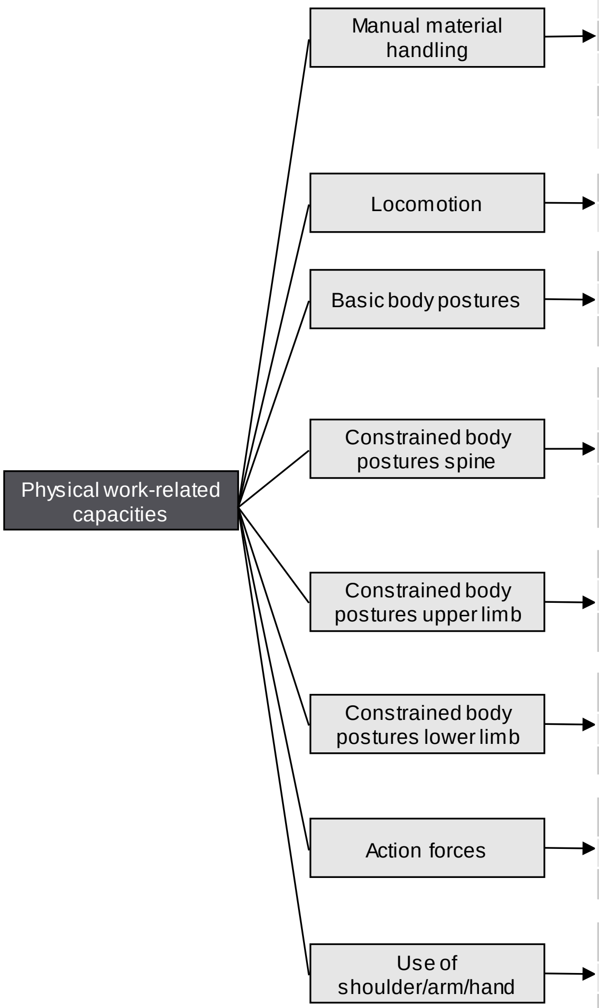
A pair comparison of the skill profiles of healthy employees by Rademacher *et al*. and employees that have changed performance by Wittemann revealed differences in several skills for both groups (Scheller *et al.*, 2015, p. 142). While for healthy workers 25% (in absolute numbers 8) of the tested abilities showed a significant difference and for the ability limited workers 78% (32) of the tested abilities showed significant differences (Scheller *et al.*, 2015, p. 142; Landau *et al.*, 2012, p. 82). Even though the study of healthy employees found fewer significant age dependencies overall several work activities could be performed significantly worse by older workers (Rademacher *et al.*, 2013, pp. 246–247). Especially in the categories strong bending and manipulation of weights greater than 5 kg, significant differences were available in both studies. Further, for the healthy collective it has been shown that for a load weight of over 15 kg the median of assessment reached its maximum indicating that most elderly workers had severe limitations (Rademacher *et al.*, 2013, p. 239).

2.3.2.2 Qualitative summary of age-related changes relevant in industrial work

Based on the studies conducted across different industries a clear picture of industry relevant skills and their age-related changes become visible. Psychological and cognitive changes are mainly described as performance increasing. Further, while there is a low evidence for impacts of sensory abilities for industrial work tasks, physical workload, the strain reaction and several physical abilities are strongly linked to age-related decline.

Based on the introduced classification of industrial worker abilities, Figure 17 shows an overview of different skills and the relevance of aging on their change for industrial work. The classical notation of significance levels (*** $p \leq 0.001$, **$p \leq 0.01$, * $p \leq 0.05$, ° $p \leq 0.1$) is used to indicate the relevance for age on different abilities. The column “Age 1” refers to the studies of Rademacher 2011 and 2013 with healthy employees and column “Age 2” to the studies of Wittemann 2017. For some abilities no test data were available from literature (marked as X in Figure 17).

The literature discussion outlined here, clearly shows that the issue of changes in industry-relevant skills in an ageing workforce were only addressed little so far (Landau *et al.*, 2007b). Most results are available for the automotive sector with highly standardized processes and might therefor be of limited transferability to other sectors. However, the studies conducted by Rademacher and Wittemann prove that there are significant differences between most work relevant abilities of younger and older workers in the automotive industry considering healthy as well as already ability limited samples. However, these studies do not provide a quantification of the related ability changes. Therefore, it can be concluded that there is a low level of meaningful data in literature witch allow quantitative and detailed propositions concerning the age dependency of the performance capability of workers in an industrial work setting and currently no conclusions for operational practice can be drawn (Wittemann 2017, p.21).



Ability	Age 1	Age 2
Lifting from flor to waist	**	***
Lifting from waist to head	**	***
Lifting horizontal	x	x
Carrying	x	***
Holding	x	***
Pushing and Pulling	x	***
Walking	x	***
Climbing (stair/ladder)	x	***
Standing	x	°
Sitting	x	***
Lying	x	x
Bent forward (20-60°)	°	
Strongly bent (>60°)	*	**
Trunk rotation	x	*
Lateral bending	x	*
Movement of head/neck	x	x
Elbow at shoulder level	°	***
Hands above head level	**	x
Far reaching	x	x
Kneeling	x	***
Squatting	x	***
Crawling	x	x
Finger hand forces	x	**
Whole body forces	x	*
Impulse / Shock / Vibration	x	x
Arm / wrist movement	x	**
High repetitive work	x	x
Precision work (dexterity)	x	x

Figure 17: Abilities relevant for manufacturing and logistics workplaces (own representation, model based on Tittor *et al.*, 2004, p. 212, Müglich *et al.*, 2015a, 3, age-related dependencies based on Rademacher *et al.*, 2013, Scheller *et al.*, 2015, Wittemann, 2017, pp. 44–57)

2.3.2.3 Studies specifying work-related ability changes of elderly workers

In relation to a quantification of age induced changes of worker abilities literature shows that most existing studies only focus on changes in maximum capabilities and are carried out in laboratory settings (Silverstein, 2008). This allows limited conclusions for work design and operational practice (Börner *et al.*, 2017, p. 4; Wittemann, 2017, p. 21). Thus, the literature presents no satisfying findings of significant influences of age on work related physical worker abilities. The quantitative influences of age on industry relevant worker capabilities is barely evaluated (Rademacher *et al.*, 2013, p. 231; Wittemann, 2017). However, some studies providing insights in industry related samples are summarized in this section.

DeZwart *et al.* conducted a cross-sectional questionnaire survey of over 44.000 employees in the Netherlands to evaluate the effects of ageing and physically demanding work on musculoskeletal health complaints. They found an increase in the prevalence of musculoskeletal complaints with age and identified an average decline in muscular capacity of 10–25% at 65 years. However, they concluded that this change is not consistent and very variable dependent on BMI and leisure time activities (DeZwart *et al.*, 1995)

Gall and Parkhouse conducted a study in which work-specific tests for the mapping of physical workloads were developed and applied for high-voltage technicians. The work-specific experiments were designed to be representative for the physical workload of this occupational group on the basis of a conducted work analyses. A comparison of a total of 40 younger (≤ 39 years) and older (> 50 years) workers showed that in six out of nine tests no significant differences were found in the mean values of the respective test variables between the age groups. The group of older test subjects only showed significantly lower values for maximum oxygen intake, one-handed isometric "pull down" with maximum force and maximum isometric hand force. Nevertheless, they conclude that the older high voltage technicians are able to cope with the demands of their work and add that heavy physical work can even maintain the performance related to the respective activity in old age. (Gall and Parkhouse, 2004)

Savinainen *et al.* examined the age-related development of physical performance in two company samples over ten and 16 years, respectively. They identified a significant reduction in spinal flexibility, a decrease in trunk flexion and extension strength with increasing age. Although the results resemble a deficit model of ageing, they also point out the ability to compensate for declining physical performance characteristics (Savinainen *et al.*, 2004).

Walch conducted a survey in logistics, where human resources and general management were asked to subjectively rate different abilities of older worker for operational logistics. The results of this study mainly resemble the findings from literature described beforehand, but put a stronger focus on logistic work. Walch 2012 found that overhead work, decreasing maximum static forces, physical capacity of lifting and carrying, as well as abilities including bending and twisting of the trunk are seen as the abilities that strongly diminish with increasing age. Further, physical capacity in pushing and pulling strength, the ability to conduct basic body movements, the capacity to lift loads, and the flexibility of the hand arm system were judged as strongly decreasing with age (Walch, 2011, p. 65). Finally, a survey with 32 managers from operational logistics revealed that for the elderly workers (45+) the existing physical stress and the adaption to change are the most relevant problems in occupational practice (Walch, 2011, p. 69). However, this study is based solely on management perception and not physical measurements.

Kenny *et al.* collected numerous scientific findings in an extensive literature study on age dependence of basic physiological functions, such as maximum muscular strength and maximum oxygen uptake, or on age-related changes in the musculoskeletal system, such as flexibility and stability of the spine. They also considered the effects of the aging process on performance. Based on their research, they come to the conclusion that age-related reductions in employee performance can be partly counteracted by continuous physical training (Kenny *et al.*, 2008).

In a study with approximately 1,500 workers, Hamberg van Reenen *et al.* observed parameters of muscular performance. It was found that the static endurance of the neck and shoulder muscles was most pronounced in the oldest employees. In contrast, the static endurance of the back muscles showed a reversed U-shaped course over the age with a maximum at 36 years. In addition, the younger employees, who were active for more than three hours a week, were certified as having the best performance. Among the older employees, those who exercised up to three hours a week had better muscular performance than those who did not exercise or were active for more than three hours a week (Hamberg van-Reenen *et al.*, 2009).

Landau *et al* report a study with 4000 rehabilitation patients where the dependency of work and occupation-related performance values on the sector of work and age were evaluated for 28 different abilities relevant for work. They conclude slight linear losses in performance with increasing age within the occupational group of retailers and service, U-shaped progressions with the lowest values between 46-51 in assembly jobs and declining skills for construction workers till the age of 51 (Landau *et al.*, 2007b, pp. 25–31).

In relation to specific abilities (Chung and Wang, 2009) highlighted age-related declines in joint mobility, mainly in relation to the spine and wrist and (Pennathur *et al.*, 2003) proved the same for manual dexterity. Overall flexibility an range of motion decreases with age, implying an impact on specific tasks as bending, stooping and similar (Varianou-Mikellidou *et al.*, 2019, p. 233).

Caused by declining performance of the cardiovascular and respiratory systems after the age of 25 years[6] also the physiological performance and the aerobic capacity decrease. The physiological performance peaks between ages around 25 years of age and afterwards declines by 1% per year according to previous studies (Ilmarinen, 2002a; Ilmarinen and Rantanen, 1999; Salthouse, 2000; Warr, 1994) . The aerobic capacity also decrease after the age of 25 and even more after age 40 (Kenny *et al.*, 2016; Kenny *et al.*, 2008; Kowalski-Trakofler *et al.*, 2005; Shephard, 2000; DeZwart *et al.*, 1995), reducing the ability to conduct exhausting work over a longer period of time.

Also muscle peak force, muscular power and dynamic actions with force decrease with age, starting at the age of 20 (EUOSH, 2016b; Kenny *et al.*, 2008; Kenny *et al.*, 2016; Savinainen *et al.*, 2004; Zwart *et al.*, 1997; Aoyagi and Shephard, 1992). This can lead to working closer at strain limits in material handling tasks.

2.3.2.4 Quantitative summary of age-related changes relevant in industrial work

In Table 3 important changes of human abilities with age are summarized, also quantifying the average change of the ability where possible. Further, possible impacts at work are named, according to studies.

Table 3: Studies exploring work relevant abilities [adapted from (Varianou-Mikellidou *et al.*, 2019, pp. 234–238)]

Abilities	Description / Quantification	Possible impact at work	Source
Physiological function overall performance	• Peaks at age 30, then declines by 0.75–1% per year with an overall loss of about 20% between the ages 40 and 60 • Most physical abilities peak around the age of 20years and decline afterwards by 1% per year. • Physical work capacity of a 65-year-old can be reduced by up to 50%compared with an average 25-year-old worker • Maximum physical performance declines by about 1.5% per year.	Physical or mental decline impacts performance on most work, until age 70, with the exception of jobs requiring quick reactions or physical strength. Increasing strain at same load levels expectable	Ilmarinen, 2002a Ilmarinen and Rantanen, 1999 Salthouse, 2000

[6] EUOSH, 2016b; Savinainen *et al.*, 2004; Gall and Parkhouse, 2004; Ilmarinen, 2002a; Ilmarinen, 2001; EU-OSHA, 2012; Noone *et al.*, 2014; Schieber, 2003; Nelson *et al.*, 2010; WHO, 1993

Table 3 cont: Studies exploring work relevant abilities [adapted from (Variano-Mikellidou *et al.*, 2019, pp. 234–238)

Abilities	• Description / Quantification	Possible impact at work	Source
Cardiovas-cular and respiratory systems	• Declines progressively in both men and women by 10% per decade • Decreases by about 1–2% a year after the age of 30 years	Working near to their own maximum levels resulting in fatigue. Increasing strain at same load levels expectable Decreased tolerance to extreme heat and cold. Difficulties in adjusting to temperature differences.	EUOSH, 2016a Gall and Parkhouse, 2004 Savinainen *et al.*, 2004 EU-OSHA, 2012
	• Between age 30 and 65, functional breathing capacity is reduced by 40%		Noone *et al.*, 2014 Schieber, 2003
Cardiovas-cular and respiratory systems	• Average decline of 8% in maximum oxygen consumption per decade between the ages of 30 and 69 years in healthy white colour workers	Working near to their own maximum levels resulting in fatigue. Increasing strain at same load levels expectable Decreased tolerance to extreme heat and cold. Difficulties in adjusting to temperature differences.	Nelson *et al.*, 2010
	• There is a 50% decline in ventricular filling between the ages of 20 and 80 and the maximum heart rate decreases with age. • Decreased lung elasticity and an increase in residual lung volume from 20% of total lung capacity at age 20–35% at age 60. There is an average decline in vital capacity of 26 ml per year for men and 22 ml per year for women from age 20 to age 80		WHO, 1993
	• Reduced ability to regulate body temperature		EUOSH, 2016a
Endurance (Aerobic Capacity)	• 10% loss per decade. In machine-paced tasks, the standard rate demands 80% of the sustainable aerobic capacity of a 40-year-old worker	Working near to their own maximum levels resulting in fatigue faster. High workplace requirements might over-strain the worker	Shephard, 2000
	• It peaks in the 20s, and declines by 1% per year thereafter		DeZwart *et al.*, 1995
	• At age 65 it is 70% of that at age 25		Kowalski-Trakofler *et al.*, 2005
	• It decreases by about 5-10% per decade after the age of 25 years. After the age of 40, by about 10-15% per decade		Heath *et al.*, 1981
Peak Force (Muscular Strength)	• It peaks (100%) between the ages of 25 and 30. By age 40, 95%; by age 50, 85%; by age 65, 75% • It peaks at age 20, then decreases by 10% per decade until 60	Implications for physically demanding jobs as manual handling is involved especially for static work. Increasing strain at same load levels expectable If ability is low compared to the workplace requirement there is an increased risk of developing MSDs.	Aoyagi and Shephard, 1992 Ilmarinen, 2001 Gall and Parkhouse, 2004 Mazzeo2000 cited from (Boenzi *et al.*, 2015)
	• It peaks between the age of 20 and 30, then decreases by 1.5% per year age of 50-60. Afterwards the decline rate raises to 3% per year		Hollmann and Strüder, 2009 Scherf, 2014
	• Reduction in muscle strength (a loss of around 20–40% • between the ages of 20 and 60 years)		EUOSH, 2016a
Dynamic Actions / Force (Muscular endurance and power)	• Reduction in muscle endurance (a loss of around 20–40% between the ages of 20 and 60 years)	Relevant for all types of manual material handling tasks. Increasing strain at same load levels expectable.	EUOSH, 2016a
	• Decline 10% greater than decline in muscular strength between the ages of 20-80		Kenny *et al.*, 2008
	• The leg forces are needed for dynamic work (e.g. lifting from the squat, pushing, carrying). It decreases by about 5% per decade after the age of 20.		Lindle *et al.*, 1997
	• Gripping forces peak around the age of 35 and thereafter decrease by about 5% per year. At age 65 75-80% of the maximum value remains.		Hank *et al.*, 2009
Awkward Postures (Flexibility	• It decreases 20% to 30% from age 30 to 70	May affect jobs where people use a wide range of movement and jobs where manual handling is involved. If ability is low compared to the workplace requirement there is an increased risk of developing MSDs.	Johns and Wright, 1962; Chapman *et al.*, 1972
	• Flexibility decreases after the age of 25. By age 35, 90%, by age 50, 80%, by age 70, 70%.		Brown and Miller, 1998
	• Reduces mobility and stiffer joints, increased bone fragility		Scherf, 2014

2.3.3 Implications for workplace design

As mentioned beforehand most physical abilities decline with age. As a result the average physical work capacity of a 65-year old is about half of an average 25-year old worker (Kenny *et al.*, 2008, p. 612). Most probably outcome for the elderly worker, is a higher physical strain leading to overstraining work and long term to health impairments. Apart of that, physiological performance decline of the overall performance might affect any type of tasks and jobs and especially jobs that require the use of much physical energy (Varianou-Mikellidou *et al.*, 2019, p. 233). It has been shown that the physical capacity to perform work and maximum oxygen consumption declines as a function of age (Funk and Schneider, 2012). Insufficient rest or recovery time may negatively impact physical performance or productivity and increase the risk of work-related injury and long-term physical health effects (DeZwart *et al.*, 1995). Table 4 shows general limits to classify work according to caloric costs, oxygen consumption, heart rate, and perceived exertion.

Table 4: Classification of physical work (own representation based on Sharkey, 2008, p. 4 und Astrand, 2003, p. 521, cited from Rinnerhofer, 2012, p. 46; Pollock *et al.*, 1998, p. 987; Szymanski, 2006, p. 24

Classification	Caloric cost	Caloric cost	Relative aerobic strain	Oxygen intake	Heart rate	Maximum heart	Strain	Risk
Workload	[kcal/min]	[kJ/8h]	RAS [%]	[l /min]	[1/min]	rate [%]	RPE	Area
Light	<2.5	<4200	0-15	<0.5	<90	35-54	<9	Green
Moderate	2.5-5.0	4200-6300	15-22	0.5-1.0	90-110	55-69	9-11	Yellow
Heavy	5.0-7.5	6300-8400	22-30	1.0-1.5	110-130	70-89	11-13	Orange
Very heavy	7.5-10	>8400	30-50	1.5-2.0	130-150	≥90	13-15	Red
Extremely heavy	>10		>50	>2.0	150-170		15-17	Red

Several studies linking different occupations to the average caloric cost are presented in (Rinnerhofer, 2012, p. 58; Ainsworth *et al.*, 1993, pp. 76–77; Ainsworth *et al.*, 2000, pp. 500–501). To compare activities often the caloric costs normalized to the individual body weight. This index is called the metabolic equivalent (MET) and is calculated as caloric cost divided by the body weight. Therefore 1 MET corresponds to 3.5 ml of oxygen consumption per kg body weight and minute for the average adult men and 3.15 ml of oxygen consumption per kg body weight and minute for an average woman (Rinnerhofer, 2012, p. 18). The advantage of specifying energy expenditures in MET is that parameters such as age or gender can be taken into account (Ainsworth *et al.*, 2000, p. 502). According to age differences have been found within the caloric costs normalized to the individual body weight as illustrated in Table 5. It can be seen that the limit values work decline with increasing age independent from the workload level.

Table 5: Classification of job intensity over age by means of MET [data from Pollock *et al.*, 1998, p. 987 for average men]

Classification	Absolute intensity METs	Absolute intensity METs	Absolute intensity METs
Workload	Young (20-39 yrs)	Middle (40-65 yrs)	Old (65-79 yrs)
Light	<2.4	<2	<1.6
Moderate	2.4-4.7	2-3.9	1.6-3.1
Heavy	4.8-7.1	4-5.9	3.2-4.7
Very heavy	7.2-10.2	6-8.4	4.8-6.7
Extremely heavy	>10.2	>8.5	>6.8

Related to energy consumption Zülch 2010 stresses in an example for logistics work that in moderate to heavy physical work performance reductions of up to 8% can emerge within 20 years. For heavy work a possible performance decrease of up to 23 % within 37 years is calculated. In this model the decline in relation to physical work results in a reduction in the ratio of the specified times to real execution times in the range of 7 % to 23 % with increasing age. Zülch concluded that this is not only a serious ergonomic problem, but also as a business management problem (Zülch, 2010, pp. 405–406). This means that many job categories with a high physical workload, as well as with a share of elderly or female workers, could represent a health hazard (Ilmarinen *et al.*, 1991, p. 108). Therefore, the working energy turnover should be lowered for such workers. General limits in terms of working energy expenditure for heavy physical work are summarized in Table 6

Table 6: Working energy limits for the classification of heavy physical work [kcal/min] (Rinnerhofer, 2012, p. 50)

Author	Working energy expenditure in [kcal/min]	
	Male	Female
Sharkey und Davies 2008, Astrand 2003	5.0-7.5	
Müller 1962, Lehmann 1962, Frauendorf 1981	4.0	
Blink 1969, NIOSH 1981	5.0	3.5
Triebig et al. 2011	3-4	2-3
Schmidt und Lang 2007	3.3	2.6
Münzberger 2012	4.0	2.8
Schwerarbeiterverordnung AUT (BGBL II 2006/104)	4.0	2.9
Rinnerhofer 2012, 33% VO_{2max}	7.6 ± 2.0	5.3 ± 1.1
Rinnerhofer 2012, 50% VO_{2max}	7.2 ± 1.5	4.7 ± 1.1

For moderate to heavy physical work the oxygen consumption in liter per minute is constantly linked to working energy expenditure expressed in kJ, so that the working energy consumption can be used as a predictor for the physical work strain (DGAUM, 2013, p. 10; Rinnerhofer, 2012, p. 29)[7]. The relative aerobic strain (RAS) is defined as the oxygen consumption during work related to the maximal oxygen consumption VO_{2-}-max (Ilmarinen, 1992a, p. 57). Scientific literature recommends that the relative work strain should not exceed 33% to 50% of a the individual maximum oxygen intake (Prskawetz *et al.*, 2006; Rinnerhofer, 2012, p. 20; Astrand, 1960; Hofmann *et al.*, 2004, pp. 104–105). In relation to this, Figure 18 shows a comparison of three different measurements of submaximal workload (absolute heartrate (W130), rating of perceived exertion (WR13) and 80% of relative HR (Wp80)) compared to the maximum oxygen intake (VO_2-max) and age. As can be seen in the figure, the performance at constant stress and strain levels declines with age correlating to the VO_{2-}-max reduction.

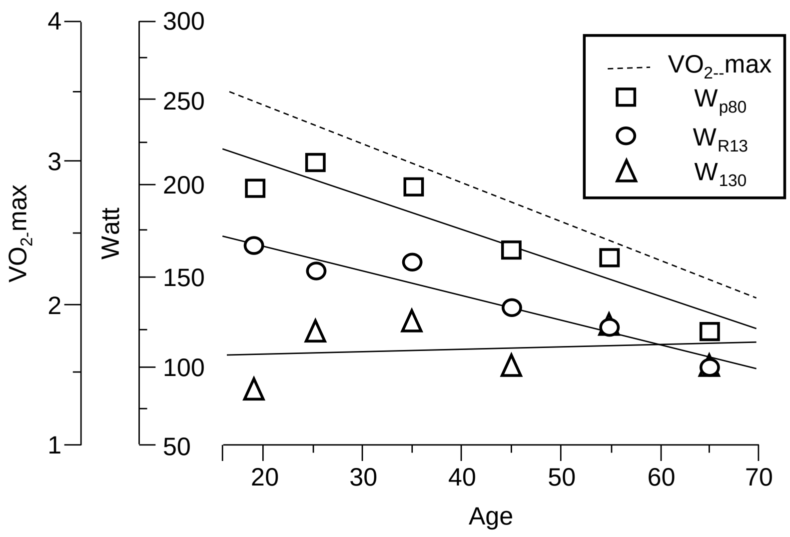


Figure 18: Relation of performance, oxygen intake and age (Borg, 1998)

[7] Energy expenditure [kcal] = Oxigen consumption [l] x 4.85 x time [min]

Ilmarinen 1992 concluded from his study that, for work with an oxygen consumption of 1.0 liter per minute in 63% of female workers aged 55 years and older work at minimum 50% RAS, and 75% of male workers work at RAS levels of 33% or higher. Therefore, it should be noted here that a VO2 level from 0.7 to 1.5 liter per minute at work can already be a heavy physical load for an older person (Ilmarinen, 1992b, p. 72).

However, workloads of that range of oxygen consumption are quite usual in physically demanding work such as metal industry, meat industry, waste and recycling industry etc. (Rinnerhofer, 2012, p. 122). For example, in construction work, absolute oxygen consumptions of 1.1 litre per minute or more have been reported, which corresponds to 25% of the VO_2_max for younger and 33% of VO_2_max older workers (Jebens *et al.*, 2015). For the older workers, this relative work rate approaches and may exceed the upper limits (30%–35% VO_2max) of relative energy expenditure recommended for an 8h shift (Kenny *et al.*, 2016, p. 10). However, higher work intensities will expose the older workers to greater relative strain, and therefore increased risk of injury because of overexertion and fatigue (Kenny *et al.*, 2016, 101). To avoid such injuries and fatigue, older workers will likely require longer rest or recovery periods following intense work activities than their younger counterparts (Kiss *et al.*, 2008).

The remarkable reduction of muscle strength or peak force, muscular power or dynamic actions with force, might have similar effects as reduced endurance regarding physical work (Varianou-Mikellidou *et al.*, 2019, p. 233). Further, the highly significant difference in the capabilities to lift a loads over 5 kg can negatively influence most manual material handling activities in industry. The decreasing endurance and aerobic capacity after the age of 25 and even more after age 40 might affect the ability to do physical work over extended periods as well as perform physically intensive tasks (Varianou-Mikellidou *et al.*, 2019, p. 233). Additionally, due to a decrease flexibility and the ability to work in constrained body postures as well as a decreasing range of motion decreases muscle pain might make several tasks more difficult (Varianou-Mikellidou *et al.*, 2019, p. 233). The changes in circadian adjustments can negatively impact on shift and night work where older workers might face sleep problems. (Varianou-Mikellidou *et al.*, 2019, p. 238). In particular, changes in hearing, vision and in balance have been found to increase to risk of injuries as there is a possibility to miss alarms or other signals, especially when the workplace has caused the hearing loss (Varianou-Mikellidou *et al.*, 2019, p. 238). Further, visual changes might have an impact on detailed tasks, on adapting to changing lighting conditions, including the ability to follow visual targets, notice the difference between blue-black and the sensitivity to glare (Varianou-Mikellidou *et al.*, 2019, p. 238). High visual requirements at close range pose increasing strain for elderly workers even though they can be usually compensated with (reading) glasses (Börner *et al.*, 2017). Changes in balance might result in higher risk of slips, trips and falls. This can be counteracted by marking steps and ramps, avoiding slippery walkways and illuminating workplace (Varianou-Mikellidou *et al.*, 2019, p. 238). In addition, the introduction of new information technologies, due to a lack of user knowledge on the part of older employees reduces the availability of existing experts. Moreover, aging workers must face the change in the nature of work where work organisations, work methods and tools, as well as workloads are changing faster than human resources can easily adapt causing more problems than positive challenges for the aging workers (Ilmarinen, 2001, p. 548).

2.3.4 Interim conclusion age-differentiated limit values for work design

As shown by several authors general limit values for all age group often do not meet the individual requirements of different age groups. Therefore, age-related limit values are advisable (Merkus *et al.*, 2019, p. 305). For **body postures** different limit values are available in literature. Risk assessment and limits for high risk can be derived from the IAD methods (BKB, AWS-light, AAWS, EAWS, see section 2.4.3). Age-differentiated risk values are not available for different body postures in literature. For **load**

handling age- and gender-differentiated limit values are available in literature. While the limit values differ by 5 to 10 kg according to different authors, limits for lifting and carrying for an older population (45+) are always lower than the values for younger groups (see (Günthner *et al.*, 2014, p. 71; Kerschhagl and Koller, 2013, p. 30)). Further, limit values for light duty workplaces for ability limited workers were released by (Wittemann, 2017, p. 89). For the overall physical workload limit values for heavy work are available according to the working energy expenditure, oxygen consumption and heart rate. Further, age-differentiated limit values are available for environmental conditions as lighting or temperature. In Table 7 different age-differentiated limit values are listed in comparison to the general limit values from standards or international recommendations. This values can be used for preventive workplace design or assessment.

Table 7: Age-differentiated limit values

Category	Specification	Male		Female		Source
		Young 19-45	Older >45	Young 19-45	Older >45	
Body postures						
Kneeling / squatting	Healty workforce	Low forces	Forbidden	Low forces	Forbidden	Hell et al. 1985 cited from Prasch, 2010
	Ability limited workers	Never	Never	Never	Never	Wittemann, 2017, p. 89
Bending / twisting	Ability limited workers	Never >60° Rarely >20°	Never >60° Rarely >20°	Never >60° Rarely >20°	Never >60° Rarely >20°	Wittemann, 2017, p. 89
Overhead work	Healthy workforce	According to DIN 33411-5	Rarely with forces < 10 N	According to DIN 33411-5	Rarely with forces < 10 N	Hell et al. 1985 cited from Prasch, 2010
Body movements						
Basic movements	Distribution	n.a.	Walking and sitting (each min 10%)	n.a.	Walking and sitting (each min 10%)	Hell et al. 1985 cited from Prasch, 2010
Arm movement	Reaching distances	n.a.	Grab distances < 60 cm, Grab height > 56 cm	n.a.	Grab distances < 60 cm, Grab height > 56 cm	Hell et al. 1985 cited from Prasch, 2010
Physical workload						
Energy turnover		16.5-17.5 kJ/min	n.a.	11-12 kJ/min	n.a.	Bokranz and Landau, 2012, p. 261
Oxygen consumption		1.4 l/min O_2	0.7 l/min O_2	1 l/min O_2	0.5 L/min O_2	Ilmarinen & Tempel 2002, Schmidt & Lang 2007
Oxygen consumption		55% RAS	55% RAS	55% RAS	55% RAS	Rinnerhofer, 2012, p. 111
Heart rate (HR) as percentage of the maximum heart rate		<50%	<35-39%	<50%	<35-39%	Ilmarinen, 2001, p. 547, Ilmarinen, 1992a, p. 74
Load handling						
Carrying	Occasionally (<1/2 h or 5% of shift)	50 Kg	40 Kg	15 Kg	13 Kg	Hettinger 1991, Terhaag 1985 cited from Kerschhagl and Koller, 2013, p. 30 Günthner *et al.*, 2014, p. 71
	Middle (<1h / 10% of shift)	30 Kg	25 Kg	10 Kg	9 Kg	
	Often (>1h / 10% of shift)	20 Kg	15 Kg	10 Kg	8 Kg	
Lifting	Occasionally (<1/2 h or 5% of shift)	55 Kg	50 Kg	15 Kg	13 Kg	Hettinger 1991, Terhaag 1985 cited from Kerschhagl and Koller, 2013, p. 30 Günthner *et al.*, 2014, p. 71 Pflaumbaum *et al.*, 2017, p. 201 Wittemann, 2017, p. 89 Hell et al. 1985
	Middle (<1h / 10% of shift)	30 Kg	25 Kg	10 Kg	9 Kg	
	Often (>1h / 10% of shift)	25 Kg	20 Kg	9 Kg	8 Kg	
	According to pressure in the spine	6 KN	2.3 KN	4.4 KN	1.8 KN	
	For ability limited workers	≤8-10 Kg occasionally	≤10 Kg occasionally	≤10 Kg occasionally	≤10 Kg occasionally	
Pushing	Two-handed sustained 90% percentile	230 N	n.a.	130 N	n.a.	ISO 11228, part 2
	Depending on execution (overhead to waist, f>1/min)	84-210	70-168 N	55-137	46-109 N	David and Stubbs 1978 cited from Glitsch, 2004, pp. 119–120
	For ability limited workers	≤100 N occasionally	≤100 N occasionally	≤100 N occasionally	≤10 Kg occasionally	Wittemann, 2017, p. 89

Table 7 cont.: Age-differentiated limit values

Category	Specification	Male		Female		Source
		Young 19-45	Older >45	Young 19-45	Older >45	
Load handling						
Pulling	Two-handed sustained 90% percentile	240 N	n.a.	140 N	n.a.	ISO 11228, part 2
	Depending on execution (overhead to waist, f>1/min)	126-350 N	112-280 N	82-228 N	73-182 N	David and Stubbs 1978 cited from Glitsch, 2004, pp. 119–120
	For ability limited workers	≤100 N occasionally	≤100 N occasionally	≤100 N occasionally	≤10 Kg occasionally	Wittemann, 2017, p. 89
Work environment						
Noise		> 85 dB (A) use of ear muffs	n.a.	> 85 dB (A) use of ear muffs	n.a.	Pflaumbaum *et al.*, 2017, p. 156
Vibration		0.8-5 m/s^2 hand-arm 1.15m/s^2 Whole body	elimination of vibration	0.8-5 m/s^2 hand-arm 1.15m/s^2 Whole body	elimination of vibration	Pflaumbaum *et al.*, 2017, p. 158; DGUV, 2009, p. 34
Lighting		Minimum lighting thresholds according to activity	20% more light 40-55 years, 100% more after 55 years	Minimum lighting thresholds according to activity	20% more light 40-55 years, 100% more after 55 years	Held, 2014, p. 44, Ilmarinen and Tempel 2002
Climate		Within comfort area	Within comfort area	Within comfort area	Within comfort area	Held, 2014, p. 56
Additional physical factors						
Static force	Holding	8-15% of maximum isometric strength	8-15% of individual maximum isometric strength	8-15% of maximum isometric strength		Wakula *et al.*, 2009, p. 16 Ulmer, 2001
	Weight holding	25-30 Kg	n.a.	15-20 Kg	n.a.	DGUV, 2010, p. 48
	Body forces	According to Din 33411 or Force Atlas	< 100N standing < 50N sitting	According to Din 33411 or Force Atlas	< 100N standing < 50N sitting	Wakula *et al.*, 2009 Hell et al. 1985 cited from Prasch, 2010
	Static forces whole body depending on conditions of execution	According to Din 33411 or Force Atlas	0.78-0.96 times the young male force	According to Din 33411 or Force Atlas	0.5 times the old male forces	Wakula *et al.*, 2009, p. 139

In summary, based on the age-related changes of human abilities and derived differentiated values available from literature, it is evident that general workplace design and assessment based on uniform suggestions will result in short-term physical overload and long-term health impairments for a significant proportion of workers. Ergonomic assessment methods have to incorporate the age-based differences and become age-differentiated assessment methods to include elderly workers. In addition, workplace design has to be adapted for age-based limit values to ensure safe workplaces for elderly workers. To design age-appropriate workplaces ergonomic design principles are needed, which are introduced in the next section.

2.4 ERGONOMIC WORKPLACE DESIGN

In this section the basics of ergonomic workplace design are introduced. First, requirements and regulations that apply are summarized. Second, the goals and process of the ergonomic workplace design is introduced. Subsequently, the next section deepens the knowledge in the first phase of the design process, outlining the scientific approach of the ergonomic workplace assessment. In addition, different methodologies and tools for ergonomic risk assessment are described. Next, the ergonomic intervention process is explained summarizing different general types of interventions and related measures from primary and secondary interventions. Finally, a preventive intervention process for such measures is introduced.

2.4.1 Requirements and regulations

In Europe, the protection of health and safety at work is regarded as a public responsibility. The legal basis is provided by the European Framework Directive on Occupational Health and Safety (89/391/EEC), which defines the minimum standards for occupational health and safety in the European Union (Rantanen and Fedotov, 1998, 16.4)

The directive were transposed into Austrian national law by the health and safety at work act (ArbeitnehmerInnenschutzgesetz, ASchG) (Federal Ministry of Labour, Social Affairs and Consumer Protection, 2009, p. 3). In §3 ASchG the responsibility for the safety and health of his or her employees is assigned to the employer. According to §4 ASchG, employers are obliged to identify and assess the risks for safety and health of workers and implement prevention measures where needed, taking into account the latest state of the art and knowledge in the field of work design (§3-2 ASchG). From a legal point of view, occupational ergonomics is essential to avoid penalties. Therefore, ergonomic risk assessment as described in the EU framework directive (89/391/EEC) have to be carried out in various phases of the product life cycle (cf. Schaub *et al.*, 2012, p. 616). This is a strong argument for the introduction of standardized ergonomic evaluation procedures.

The EU machinery directive (2006/42/EC) as well as the EU directive on manual materials handling (90/269/EEC) defines a maximum safety level considering essential safety requirements (ESR) (Wakula *et al.*, 2009, p. 193), which ensures a uniform level of protection when machinery is commissioned within the European Union (Schaub *et al.*, 2012, p. 616). By means of harmonized standards (CEN, ISO) these ESRs are specified and specific guidance for ergonomics and the risk assessments at shop floor level is introduced (Schaub and Landau, 2004, p. 53). The relations of the EU directives and related international standards are shown in Figure 19.

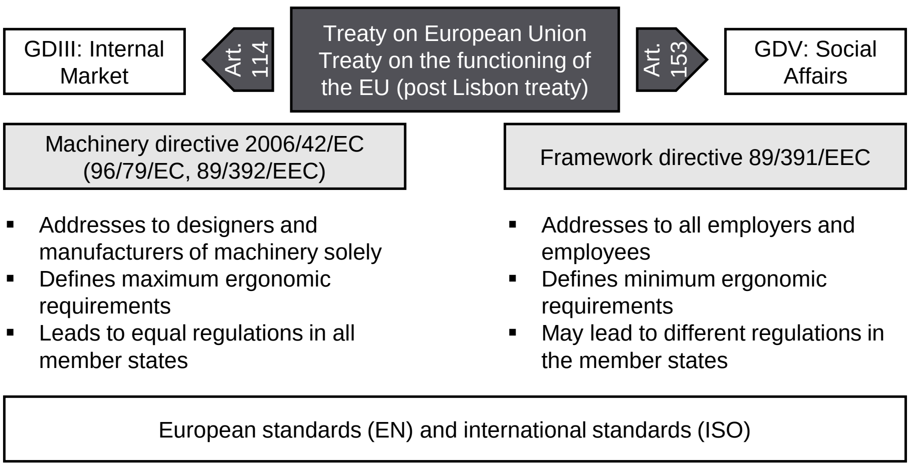


Figure 19: EU directives with relevance to ergonomics and related international standards [adapted from (Schaub *et al.*, 2012, p. 616)]

Ergonomic standardization itself is broad topic including several different scientific disciplines. Besides the standards mentioned in Figure 19, main standards in terms of ergonomic workplace design that offer basic ergonomic guidance include EN ISO 6385 - Ergonomics principles in the design of work systems, EN ISO 26800 Ergonomics - General approach, principles and concepts, EN ISO 12100 - Safety of machinery - General principles for design - Risk assessment and risk reduction, EN 614 - Safety of machinery - Ergonomic design principles and the EN ISO 9241-series Ergonomic requirements for office work with visual display terminals. Further, important standards in terms of ergonomics, workplace design and individual worker abilities and needs are illustrated in Figure 20 (based on Wolf, 2015, pp. 69–75).

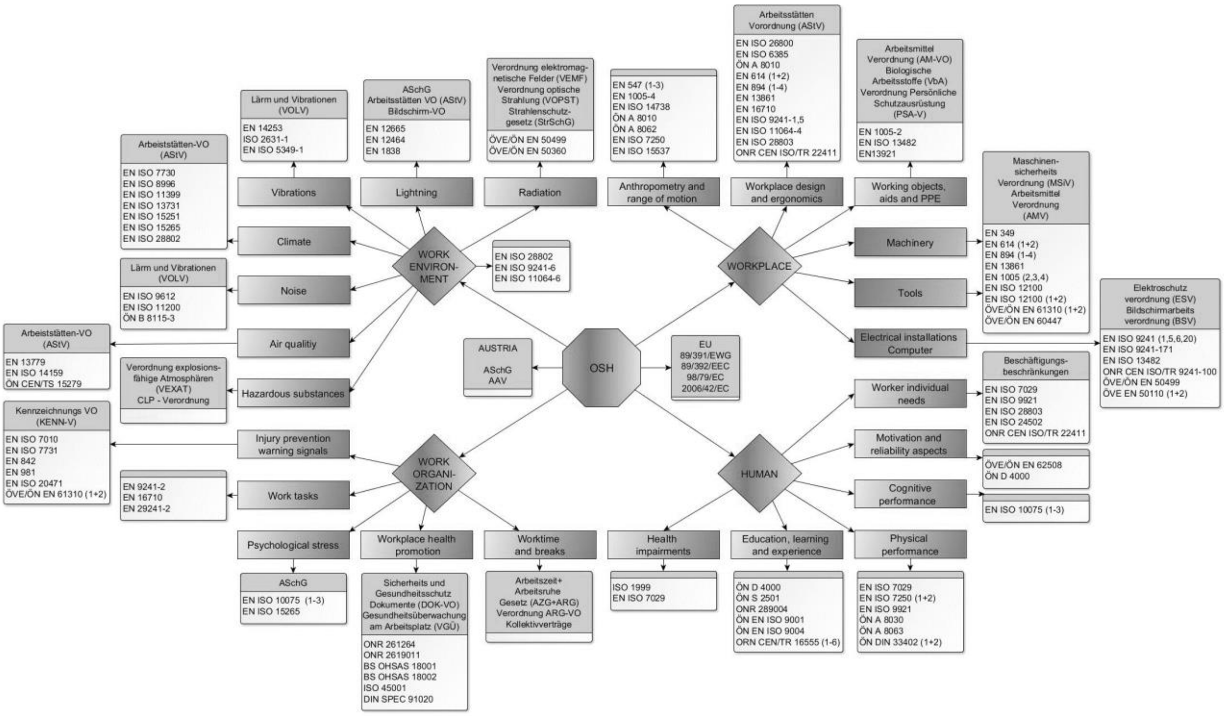


Figure 20: Important Austrian laws and regulations and important international and Austrian standards in human centred ergonomic workplace design (EN: European standard, ISO: international standard, ÖN: Austrian standard. Dark areas indicate Austrian laws and regulations)

2.4.2 Goals and process of ergonomic workplace design

According to the International Ergonomic Association *“Ergonomics is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance […] Derived from the Greek ergon (work) and nomos (laws) to denote the science of work, ergonomics is a systems oriented discipline which now extends across all aspects of human activity“* (IEA 2000 cited in Schlick *et al.*, 2010, p. 949).

Thus, the aim of ergonomic workplace design is to optimise both human well-being and the performance of the work system (Schlick *et al.*, 2010, pp. 949). The optimization of the performance of the work system is widely known under the umbrella terms, rationalization, lean management and operations management. Detailed information on the improvement tools and processes can be found in scientific literature (e.g. Slack *et al.*, 2016; Ohno, 2006). As the focus of this thesis lies in human centred work design the aim of the ergonomic design process is described in more detail.

For the optimization of the human wellbeing different impacts deriving from the work system have to be considered. Occupational science and occupational medicine evaluate activities according to the three health-related aspects executability, tolerability, and reasonability (DGAUM, 2013, p. 11). In ergonomic sciences these criteria are supplemented by two more criteria including the worker satisfaction and personal development as well as the social acceptability of human work (Schlick *et al.*, 2010, p. 67).

The **executability** of work represents the lowest level and refers to human abilities and skills. It has to be ensured that the skills are in balance with the requirements at the workplace. This requires that the work requirements are within the limits of human performance, also taking into account individual differences in limits of sensory, cognitive and motor abilities (Schlick *et al.*, 2010, p. 63). Special focus should be put on the accessibility of controls, the application of necessary physical forces or the perception of information (Börner, 2019, p. 6). Thus executability describes if the work performance can be achieved, at least in the short term, taking into account the dose, comprising of the intensity and duration of the exposure over time (DGAUM, 2013, p. 11). **Tolerability and harmlessness,** as the next criteria to consider, are given when the work can be repeated over a whole working life without suffering health impairments. (Schmauder and Spanner-Ulmer, 2014, pp.39). Therefore care must be given to the fact that the exposure is below a level that leads to medium-term (days to months) or long-term (years to decades) health problems (DGAUM, 2013, p. 11). The determining factors for the exposure in this context are the workload, the work duration and environmental conditions such as noise or climate (Schmauder and Spanner-Ulmer, 2014, pp. 39). Thus the tolerability deals with endurance limits like the continuous performance limit (Bokranz and Landau, 2012, p. 139). The level of **acceptability and freedom from impairment** is shaped by the individual perception of the work situation in a social or cultural context. This criterion is primarily based on collective norms e.g. collective arrangements (Schlick *et al.*, 2010, p. 64). Thus, this criteria deals with fitting of the work system with the expectations of the intended operators (Bokranz and Landau, 2012, p. 139), the absence of short-term stress effects (Schmauder and Spanner-Ulmer, 2014, pp. 39), and related psychophysical impairment of the well-being and the ability to recover after the stress (DGAUM, 2013, p. 11). After ensuring a reasonable work, care should be given to **worker satisfaction and personality development** by considering aspects such as motivation, recognition or leadership behaviour of individuals at the next higher level. Satisfaction at work usually occurs when the objective characteristics of the work situation correspond to individual expectations. (Schlick *et al.*, 2010, p. 64) The highest level, **social compatibility,** becomes a necessary criterion in work design if more people work together in an organization. Social compatibility in this context means the extent to which the participation of workers in the design of work systems, is envisioned. (Schlick *et al.*, 2010, p. 65).

These different criteria to evaluate work build on each other and form an evaluation hierarchy, that can be illustrated as a stairway to human-oriented work design as shown in Figure 21.

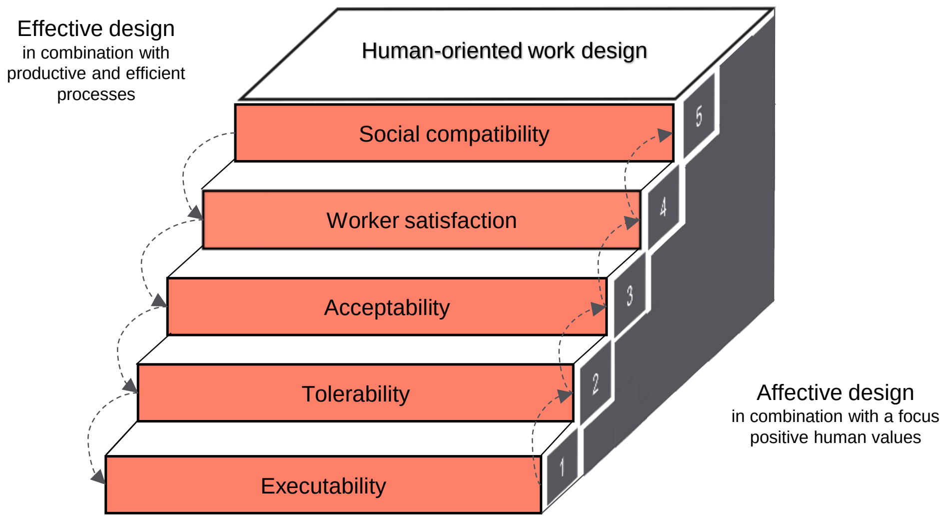


Figure 21: Criteria and connections in the ergonomics work place design process (cited from Schlick *et al.*, 2010, p. 67; Bokranz and Landau, 2012, p. 139)

This hierarchical structure builds the basis of the ergonomic design process and a framework to identify suitable measures for human centred workplace design. Following the model, ergonomic workplace design and ergonomic improvement measures have to fulfil the needs of the lower stages and aim for the highest stage (Schlick *et al.*, 2010, pp. 63-67).

After providing workplaces where the work tasks are within human capability limits (executable work) and do not lead to medium or long term health damages (tolerability), at the third step the acceptability of the work is the targeted design goal. Here, the work has to be adapted to the individual characteristics of the worker. Typical characteristics of the workplace that can be influenced are the working height and area, gripping distances, position of supply containers, environmental conditions including lighting air quality and noise, the usage of working equipment and assisting systems (Schlund *et al.*, 2018, pp. 282–283), and the functioning of machinery e.g. direction of action of actuators, shape and position of handles and controls. A comprehensive overview of measures and instructions for their implementation is provided by the relevant technical literature (see e.g. Schlick *et al.*, 2010; ÖNORM EN ISO 6385, 2016; Bokranz and Landau, 1991; Bokranz and Landau, 2012).

In the practical implementation of ergonomic workplace design different limit values are used to support planning (Schlick *et al.*, 2010, 1033, 1057). Individual employee requirements, performance changes or age effects are usually not taken into account (Spillner, 2014, p. 25). Some characteristics like gender and anthropometric data are considered within current standard procedures, but also these are taken into account on an approximate level only (Schlund *et al.*, 2018, p. 277). For body height ranges from the 5th percentile of women to the 95th percentile of men are usually used in workplace design, what means statistically that 5% of women are too small and 5% of men are too large in this context (Schlund *et al.*, 2018, p. 279). This implies that a part of the workforce has to work at unsuitable workplaces. In addition, the requirements of employees who have undergone a performance change are generally outside the scope of design specifications (Spillner, 2014, p. 25). The ergonomic design process generally consists of two stages, whereas in the first phase the assessment of ergonomic conditions according to the criteria described before takes place (Kugler *et al.*, 2010, p. 27). Results of this phase usually are ergonomic factors that are considered to impose a considerable risk. After identifying those factors, the ergonomic intervention process as the second phase of the process starts, where a solution for the problem at hand is derived (Brandl *et al.*, 2015, p. 2). The ergonomic design process including its two phases and processses is shown in Figure 22.

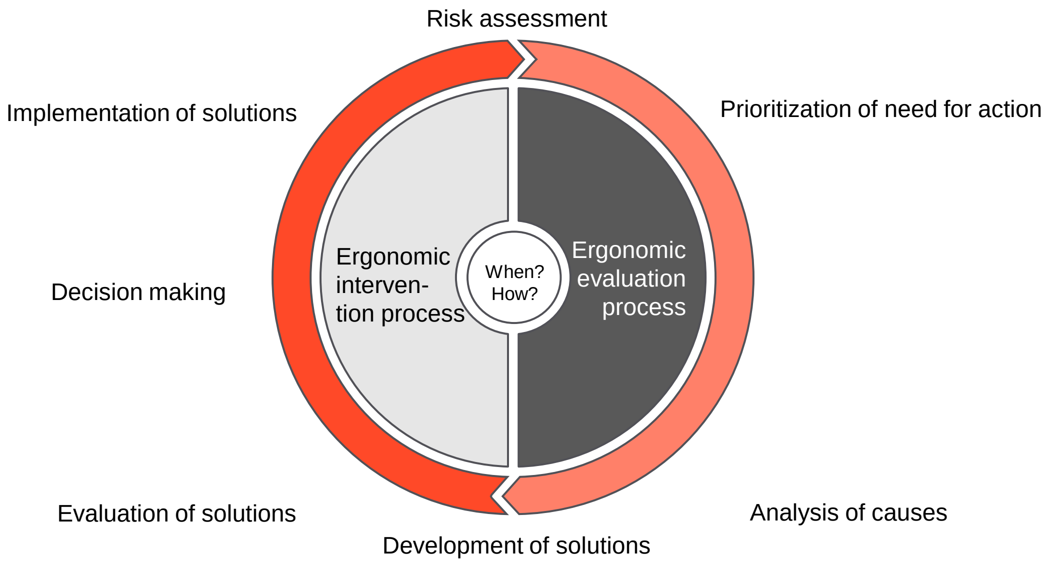


Figure 22: Ergonomic design process showing evaluation and intervention [adapted from Kugler *et al.*, 2010, p. 27]

While the ergonomic assessment process is a structures process, methodical assistance detached from ergonomic assessment methods or assistance for the ergonomic intervention process is essentially non-existent in literature (Brandl *et al.*, 2016, p. 446). According to Brandl et al. German as well as international standard literature does not include such information, making the ergonomic intervention process a highly individual and unstructured process (Brandl *et al.*, 2015, p. 2). Both parts of the ergonomic design process are described in detail in the subsequent sections.

2.4.3 Ergonomic risk assessment

The analysis of the work requirements and stresses can be carried out on a conditional or personal basis. While person-related analyses examine inter-individual differences in the experience of work (e.g. differences in the intensity of work experienced or the perception of the work task), condition-related analysis methods are objective methods, since all data is collected independently of individual characteristics (Rau, 2001, p. 6). Frequent approaches for work analysis include personal self-report by means of questionnaires and objective observation methods, as well as direct measurements (Winkel and Mathiassen, 1994, p. 983) The three types have different strengths and limitations considering work content, validity, reliability and effort needed (see David, 2005, p. 191). Especially the combination of both types in observation-interviews, conducted by experts is widely used in ergonomic workplace assessments in industry (Rohmert, 1985, Caffier *et al.*, 1999; Steinberg, 2012b.). To evaluate the risk factors in observations, different tools for the standardized identification and evaluation of physical stress and health related outcomes are available. These standardized procedures can be divided into different categories and classified according to the type of result their complexity and level of assessment, or the necessary background knowledge (Bullinger-Hoffmann and Mühlstedt, 2016, pp. 32–34; Kugler *et al.*, 2010, p. 17). In terms of the type of result the philosophy behind the method of assessment can be distinguished in methods using load limits, or different rating procedures based on a traffic light scheme (Schaub *et al.*, 2012, p. 5; Schian *et al.*, 2004, p. 235) as illustrated in Figure 23.

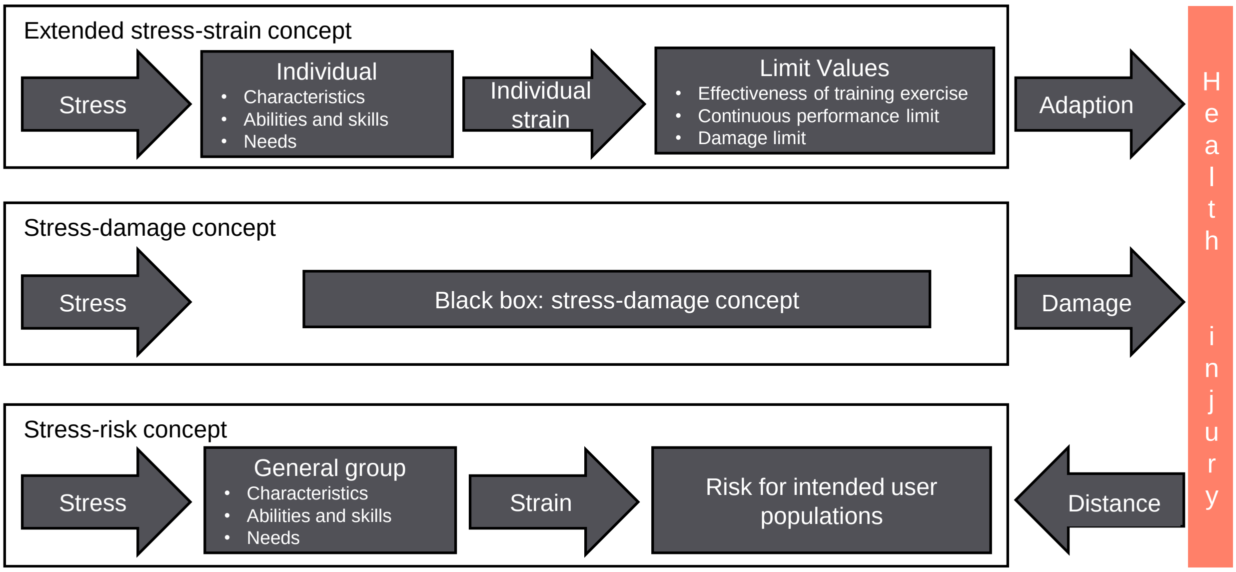


Figure 23: Basic approaches for risk assessment showing the stress-strain, the stress-damage and the stress-risk concepts used in workplace assessments [adapted from (Schian *et al.*, 2004, p. 234)]

Methods referring limit values make use of the classical stress-strain concept where an acceptable stress or strain is defined as a percentage of the maximum capacity of a reference group or an individual (Schaub *et al.*, 2011, p. 620). These procedures derive limit values as a percentage of the maximum ability capacity, taking into account personal and activity-specific parameters. Often the risk is evaluated in a two zone model in terms of acceptable or inacceptable work stress (Schaub *et al.*, 2011, p. 624). The evaluation of results is mostly done on the quotient of actual requirement to maximum or recommended ability, whereby a further distinction is possible between actual and more conservative planning analyses (Wakula *et al.*, 2009, p. 160).

Rating methods calculate a mathematical score describing the risk for a specific work tasks. Therefor pre-set weighting factors are attributed to ergonomically unfavourable situations in terms of load, duration of the exposure and these points are combined to risk values (Wakula *et al.*, 2009, p. 160). For the consideration of different user characteristics, the pre-set risk factors mostly refer to a standard worker of the intended user population. Finally, the risk scores are classified into the traffic light scheme according to the sum of points, judging the distance from actual exposure to possible health impairment (Figure 24). Dependent on the score a three zone rating system is used according to EU Machinery Directive 2006/42/EC and the standard EN 614-1 (Schaub *et al.*, 2012, p. 3). In this traffic light scheme the rating "red" symbolizes a situation where it is not possible to ensure that work can be carried out without harm, and workplace changes are indispensable. Yellow represents a medium risk level, that can cause damage, but work at such a workplace can be continued under certain conditions, such as a load-dependent job rotation. Finally, a green rating stands for low risk work places where a health impairment caused by the execution of work can be largely excluded (Egbers, 2013)

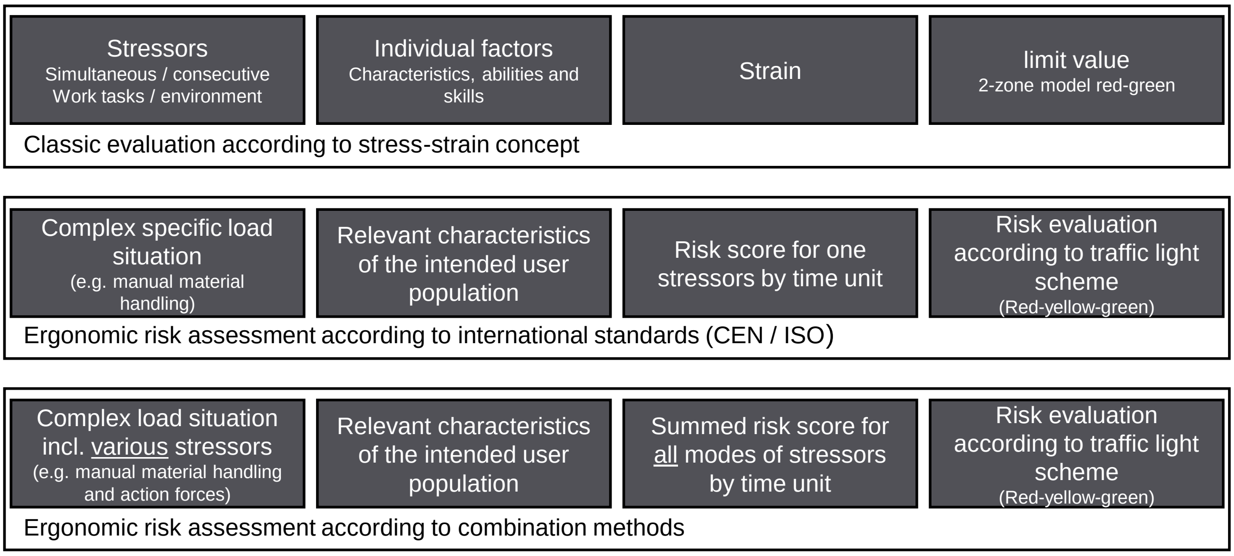


Figure 24: Different operationalization of ergonomic assessment showing the classical stress-strain approach, the assessment operationalization used in international and European standards and the procedure used in combined methods (adapted from Schaub *et al.*, 2012, p. 5; Schian *et al.*, 2004, p. 235; Schaub *et al.*, 2011, p. 620]

Based on the stress-strain concept it is assumed that the individual can adapt his abilities to a certain extent to the stress level. If the damage limit is exceeded by the available stress level a damage occurs with a probability. The stress-risk concept aims to avoid the risk of damage by an reduction of stress to an acceptable level (Schian *et al.*, 2004, p. 234).

In terms of the level of assessment a differentiation can be made in checklist, screening or detailed analyses procedures. In Figure 25 an overview of different procedures for different level of assessment is illustrated. The screening approaches are easy to use by industrial professionals, but limited to specific factors of work (Kugler *et al.*, 2010, p. 11).

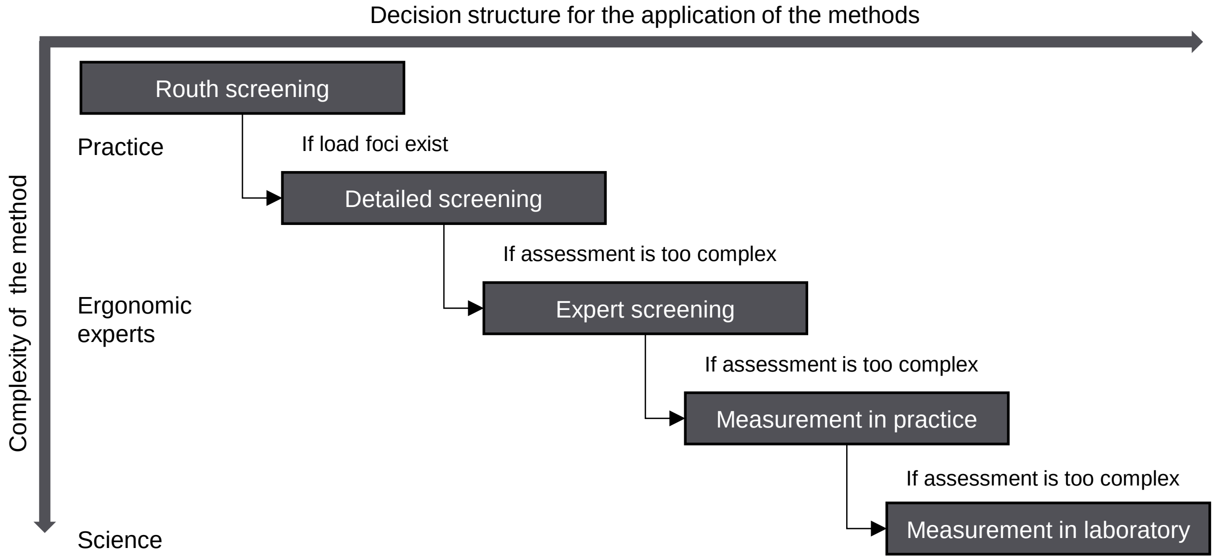


Figure 25: Structure of ergonomic assessment methods (Ellegast, 2010, p. 387)

According to industrial needs the most basic assessment procedures are different screening methods on checklist level aiming for the identification of existing main areas of exposure (Ellegast, 2010, p. 387). Rough screening procedures serve as an orienting risk assessment. They help to get an overview of several workplaces from which a risk or hazard can derive and thus allow an identification of potential risks and a pre-selection based on standard limit values (Kugler *et al.*, 2010, p. 18). These tools are easy to use and can be applied with low specific background knowledge and little training (Bullinger-Hoffmann and Mühlstedt, 2016, p. 32). Disadvantages are limited applicability in terms of varying stress situations during the work shift, complex work activities, cumulative loads, combination of stress factors and the temporal distribution of stress and recovery (DGAUM, 2013, p. 7; David, 2005, pp. 191–192).

If a specific main exposure is identified, special and expert screening methods designed for the operational practitioner and aimed at providing a risk score, can be used (DGAUM, 2013, p. 8). In contrast to the orienting methods, screening methods do not only identify possible hazards, but allow a more detailed analysis of the exposure situation. Screening methods usually provide point values which are classified and evaluated according to a traffic light system (ÖNORM EN 614-1). On the basis of these point values, problems of work design can analysed in detail and design alternatives can be evaluated and prioritized (Kugler *et al.*, 2010, p. 18). In addition, there is a number of detailed or expert procedures that typically consider one individual type of load under defined boundary conditions (Takala *et al.*, 2010, p. 6). These methods can be used to generate maximum recommended load or weight limits, often expressed as indices or point values, using an evaluation algorithm. (Kugler *et al.*, 2010, p. 18; Takala *et al.*, 2010, p. 16)

The application of screening methods is particularly suitable for cyclical process with uniform load profiles at workplaces (Ellegast, 2010, p. 387). Limitations exist in the evaluation of more complex work processes due to the roughly classified exposure categories and simultaneous consideration of different work stress (Ellegast, 2010, p. 387; Takala *et al.*, 2010, p. 16). All screening procedures and expert screening procedures have the usual limitations of observation procedures in terms of precision, exposure variability and observation sampling and observer variability (Li and Buckle, 1999, pp. 677–678; Takala *et al.*, 2010, pp. 17–18). Especially, the temporal course of stress and relief is not adequately recorded and evaluated with most screening methods (Ellegast, 2010, p. 387).

According to the type of stress and the criteria of assessment several different screening methods exist. An overview of existing procedures can be found in Takala *et al.*, 2010; David, 2005; Caffier *et al.*, 1999. Detailed descriptions of different methods, including their strengths and limitations, are given in Chiasson *et al.*, 2012; Takala *et al.*, 2010; Bongwald *et al.*, 1995. Besides validity issues discussed beforehand, a trade-off between accuracy, complexity, costs, and ease-of-use (Winkel and Mathiassen, 1994, p. 983), as well as the type of stress have to be considered when identifying an appropriate method in a particular setting (David, 2005, p. 195). Different types of physical stresses are shown in Figure 26 and major groups of assessment methods and related tools are described briefly in the following section.

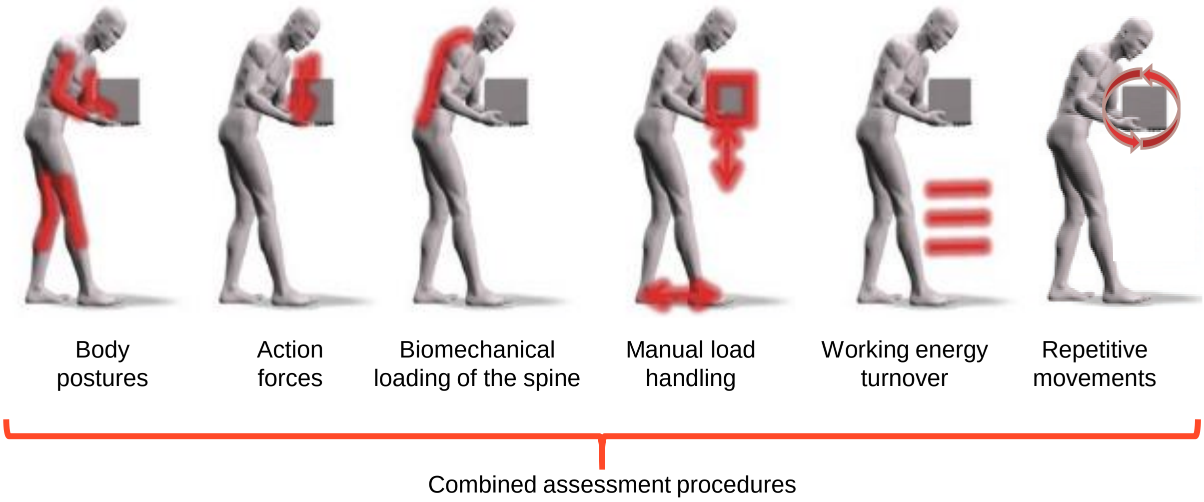


Figure 26: Different types of work stress [adapted from Bullinger-Hoffmann and Mühlstedt, 2016, p. 33]

Procedures for the analysis of body postures under consideration of certain load handling components use comfort ranges of joint angles to derive statements about the work load (Bullinger-Hoffmann and Mühlstedt, 2016, pp. 32–34). Important tools on expert level for the assessment of body postures including force application are EN 1005-3,4 and 5 / ISO 11228-3, Quick Exposure Check (QEC) by David *et al.*, 2008 and Li and Buckle, 1998, Ovako Working Posture Analysing System (OWAS) by Karhu *et al.*, 1977, and Rapid Entire Body Assessment (REBA) by Hignett and McAtamney, 2000, Loading on the Upper Body Assessment (LUBA) by Kee and Karwowski, 2001.

Generally a total risk index considering postural work load can be derived on screening level as sum over intensity of the load (R_i) and the duration of exertion of each activity (t_i) according to the following equation (cf. Schaub *et al.*, 2012).

$$R_{po} = \sum_i R_i * t_i$$

R_i ... Risk index for the activity

t_i ... duration of activity

Procedures for static body force assessment, calculate the stress based on the position of a mass or external force in relation to the body. These classical evaluation procedures derive maximum recommended action forces based on maximum static forces, taking into account person- and activity-specific parameters (Schaub *et al.*, 2015a, p. 334). Maximum forces or force percentiles (e.g. 15th or 40th) are specified in literature[8], which are related to force application points and directions in relation to the human body (Wakula *et al.*, 2009). An evaluation according to the traffic light scheme is carried out depending on the quotient of actual to recommended force (Wakula *et al.*, 2009, p. 160), whereby a distinction is made between actual and more conservative planning analyses (Bullinger-Hoffmann and Mühlstedt, 2016, pp. 32–34). Important tools within the assessment of action forces are the standards EN 1005-3 and DIN 33411-5, the Assembly specific force atlas based screening method MonKras by Schaub *et al.*, 2015b; Schaub *et al.*, 2015a, traditional German approaches based on methods as described by Burandt, 1978; REFA, 1987; Bullinger, 1994; Schultetus, 1980; VDI, 1980 and the Rapid Upper Limb Assessment by McAtamney and Nigel Corlett, 1993 the Ovako Working Posture Analysing System (OWAS) by Karhu *et al.*, 1977, the Occupational Repetitive Action (OCRA) method (Occhipinti, 1998) as well as the procedure developed by Davis and Stubbs 1977.

In generally a mathematically formulation of a risk index considering high action forces on screening level can be derived from dividing the actual force (F_{act}) by the maximum recommended force ($_c$). The maximum recommended force can be derived from multiplying the maximum static force ($F_{\max\_rec}$) dependent on a force percentile ($_{PP}$) based on tables, with a factor for the age (P_1), a factor for the gender (P_2), a factor for the frequency of force exertions (T_1), a biomechanics factor considering muscular efforts for asymmetric exertions (T_2), and a physiology factor considering frequent exertions in awkward postures (T_3) (cf. Schaub *et al.*, 2015b, p. 4).

$$R_{Fo} = \frac{F_{act}}{F_{\max\_rec}} \ldots \text{ Risk index for a forceful operation}$$

$$F_{\max\_rec} = F_{\max(pp)} * P_1 * P_2 * T_1 * T_2 * T_3 \ldots \text{ Maximum recommended force}$$

Procedures for analysis of manual load handling to determine the maximum acceptable loads can be divided in four main approaches. These are based on estimations of epidemiologic relations and biomechanical stress, physiological stress, and perceptual stress and strain (Gamberale, 1990, p. 63). In addition to the effects on humans that are considered, they differ in terms of the load and person-specific influences that are taken into account, the period under consideration and the assessment levels of human work (Bokranz and Landau, 2012, p. 195).

Epidemiological models investigate possible connections between occupational stress and its longer-term effects in the form of health impairments and thus allow a conclusion about the tolerability level (Bokranz and Landau, 2012, p. 195). **Biomechanical models** are used to analytically determine local mechanical stress in the human body and emphasize the loads on the musculoskeletal system during lifting to provide estimations of the forces and torques generated (Gamberale, 1990, p. 63). Forces in the vertebral bodies and intervertebral discs, especially in the lumbar spine, are the basis of the evaluation, thus allowing a conclusion considering the executability of the task e.g. with regard to maximum forces (Bokranz and Landau, 2012, p. 195). Limitations of the biomechanical models are primarily seen in the fact that no prediction of the work capacity is possible and that the assessment is static in nature, and limited to the sagittal plane (Gamberale, 1990, p. 63). Important tools incorporating the biomechanical approach include the "Der Dortmunder" procedure (Jäger, 1987 and Jäger *et al.*, 2000) in combination with the Mainz-Dortmunder Dose model (MDD) by Jäger *et al.*, 1999. Mathematical models for calculating the resulting load on the spine can be found in the models mentioned.

[8] Different data collections of this character are available in literature cf. e.g. Bongwald *et al.* (1995, p. 63).

Physiological models assess the tolerability of occurring loads by means of peripheral and central physiological load measurement parameters (Bokranz and Landau, 2012, p. 195). The physiological models are used to predict the **metabolic energy expenditure** in physical work tasks including manual material handling (Gamberale, 1990, p. 63). These procedures use tabular classification of different activities and mathematical calculation of estimate the energy turnover of complex activities according to qualitative criteria of load and task. (Bullinger-Hoffmann and Mühlstedt, 2016, pp. 32–34). Reference tables for different activities are available in literature (Spitzer and Hettinger, 1964) and equations for calculation working energy expenditure for different activates were developed by Spitzer and others. (Spitzer and Hettinger, 1964, pp. 66–68; Genaidy and Asfour, 1987; Garg *et al.*, 1978).These methods are useful in assessing complex activities (Bullinger-Hoffmann and Mühlstedt, 2016, pp. 32–34), but the existing models are restricted to lifting in the sagittal plane (Gamberale, 1990, p. 63) and no statements about possible longer-term consequences can be derived (Bokranz and Landau, 2012, p. 195). Tabeled average values and mathematical equations to calculate metabolic costs of lifting and carrying tasks can be found in (Spitzer and Hettinger, 1964).

Psychophysiological or **perceptual models** determine acceptability of loads and weights by determining the individual stress perception of groups of people (Bokranz and Landau, 2012, p. 195). Ratio scaling methods such as magnitude estimation is particularly suitable for studying the relation between the perception of effort and the objective work load, and the rating scale of perceived exertion is beneficial in practical settings where an assessment of the physical requirements of different work situations is needed or when interest is focused on inter-individual or intra-individual comparisons (Gamberale, 1990, p. 65). Important tools include the maximum acceptable weights value tables for different manual material handling activities according to Snook and Ciriello, 1991 and Ayoub *et al.*, 1980. And methods for the rating of the perception of loading magnitude Gamberale *et al.* or pain and effort Borg. These tables and can serve as evaluation for maximum weights for eight hour shift work according to personal perception of a load but a verification of this subjective assessment with regard to the tolerability criteria remains necessary (Bokranz and Landau, 2012, p. 195). The psychophysical scaling however can be used to identify individual differences according to the stress-strain concept (Borg, 1998, p. 24).

Screening procedures for manual material handling in terms of lifting and lowering, carrying, as well as pushing and pulling of objects calculate risk scores based on mass to be moved or the required external force as well as posture and movement measurements are especially practicable for industrial use (Bullinger-Hoffmann and Mühlstedt, 2016, pp. 32–34). Important tools include the standards EN 1005-2 and ISO 10228-1 and 2, the NIOSH equation see Waters *et al.*, 1993, the Key Indicator Method (KIM) see Klussmann *et al.*, 2017a; Steinberg, 2012a and the German approaches based on, Burandt, 1978; Schultetus, 1980; Bullinger, 1994; VDI, 1980 and REFA, 1987.

Generally, a mathematically formulation of a risk index considering manual material handling activities (MMH) on screening level can be derived from multiplying a factor for the duration (t - dependent on time, distance or amount) of exertion with factors describing the type and intensity of the load. This factors for type and intensity include the weight of the load (W), the body posture (Bp) and the work execution conditions (Wc). For the activity lifting the amount of lifts per day determines the relevant time multiplier, whereas for carrying the distance covered and for holding the time is decisive. (cf. BAuA, 2001).

$$R_{MMH} = t * R_{L,H,C}$$

$$\text{t} \ldots \text{ factor considering duration, distance or ammount of activity}$$

$$R_{L,H,C} = W + Bp + Wc \ldots \text{ Risk index for lifting (L), holding (H), and carrying (C)}$$

A mathematically formulation of a risk index considering pushing and pulling activities (R_P) on screening level can be derived from multiplying a factor for the duration (t - dependent on amount or distance) of exertion with factors describing the type and intensity of the load with the sum of factors considering the weight of the load (W) in relation to the type of pushing or pulling activity, the required precision (P), the body posture (Bp), the work execution conditions (Wc). For pushing or pulling for a distance lower than five meters the amount per day determines the relevant time multiplier, whereas for pushing or pulling over longer distances the covered distance is decisive (BAuA, 2002).

$$R_P = t * R_{PP}$$

$$\text{t} \ldots \text{ factor considering distance or ammount of activity}$$

$$R_{PP} = W + P + Bp + Wc \ldots \text{ Risk index for pushing and pulling}$$

Procedures for the analysis of (repetitive) body movements differ by the choice of characteristics to be observed considerable, but typical factors included are movements per minute, execution conditions, frequency of task changes, time of execution, and ergonomic factors (Klussmann *et al.*, 2017b, p. 3). In total 150 characteristics that can be grouped into 11 groups have been identified to influence repetitive actions of the upper limb (Steinberg *et al.*, 2012c, p. 12). However, several methods exist that calculate the risk deriving from such tasks also providing an overall assessment in the form of a risk indicator (Takala *et al.*, 2010, pp. 12–14). For the assessment of repetitive body movements in the upper limbs the Rapid Upper Limb Assessment (RULA) by (McAtamney and Nigel Corlett, 1993), the Key Indicator Method Manual Handling Operations (KIM-MHO), the Occupational Repetitive Action (OCRA) method (Occhipinti, 1998), the Hand Activity Level (HAL) by (American Conference of Governmental Industrial Hygienists ACGIH, 2001) and the Strain Index (SI) (Moore and Garg, 1995; Garg *et al.*, 2017) are the most common tools.

Generally, a mathematically formulation of a risk index considering repetitive work load on screening level can be derived from multiplying a factor for the duration (t_i) of exertion with factors describing the type and intensity of the load (F_i), force transfer/gripping conditions (Gc_i), hand-arm position and movement (Hp_i), Work organization (e.g. variation of exposures), (Wo_i), Working conditions (e.g. noise, climatic conditions), (Ec_i) and the body posture (Bp_i) according to the following equation (Steinberg *et al.*, 2012c, p. 105)

$$R_{rep} = \sum_i t_i * R_i$$

$$t_i \ldots \text{ factor considering the duration of activity } i$$

$$R_i = F_i + Gc_i + Hp_i + Wo_i + Wc_i + Bp_i \ldots \text{Risk index for the activity}$$

2.4.3.1 Overview of industrial ergonomic assessment methods

In Figure 27 the different sources of ergonomic risks at the workplace and related ergonomic standards and assessment methods are summarized. For the assessment of complex tasks in industry the consideration of a single model is often not sufficient. Therefor several models were developed that include more than one of the criteria described beforehand. These combination methods are also illustrated in Figure 27 and explained in the subsequent section.

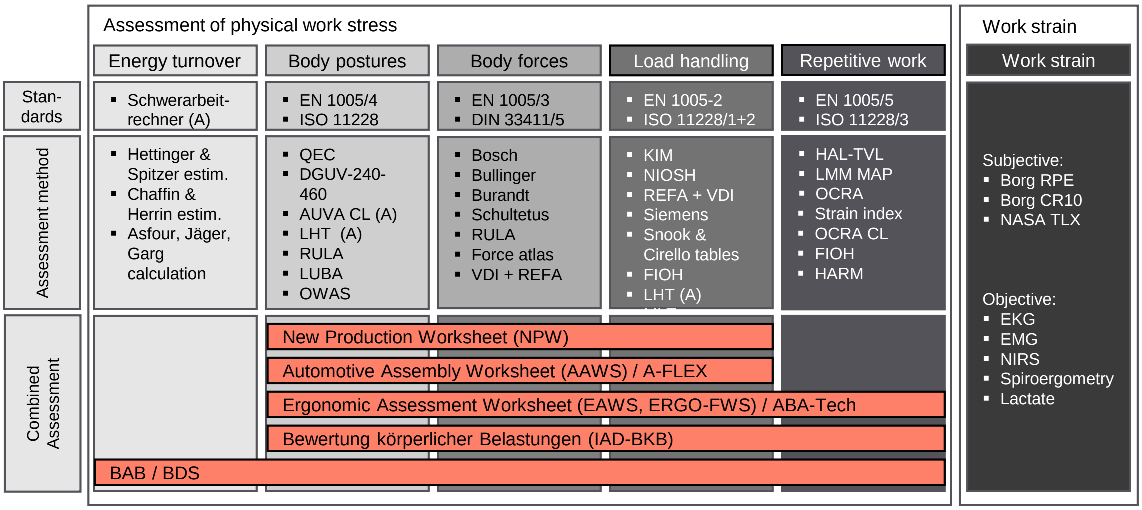


Figure 27: Overview of different assessment methods according to their main assessment areas [adapted from (Bokranz and Landau, 1991, p. 182; Börner *et al.*, 2017, p. 10; Bokranz and Landau, 2012, p. 182)]

Further, in the assessment of workplaces tools designed for a single work task often do not include all activities necessary for the assessment. Therefore, a group of combination procedures integrating the findings of several approaches or procedures and supplements them with a more comprehensive overall assessment were developed. (Bullinger-Hoffmann and Mühlstedt, 2016, pp. 32–34). The procedures a based on additive assessment of several different activities to one category to overcome the unilateral assessment of screening methods and the traditional concept of limiting values (Schaub *et al.*, 2012, p. 622). These additive assessments can concern different magnitude of load levels in manual material handling (Kugler *et al.*, 2010, p. 19) and different stress types in terms of body postures, load handling or action forces (Schaub *et al.*, 2012, p. 622). These procedures are aimed for prescribing acceptable exposure limits for workers, or at least establishing priorities for intervention across a range of tasks, but the epidemiological data upon which these scoring systems are based is limited making the scoring systems partly hypothetical (Wegman and McGee, 2004; David, 2005, p. 192).

Important methods for evaluating multitasking activities considering the handling of different load handling activities, different loads and work in different straining positions are the Multiple Load Tool (MLT) see (Kugler *et al.*, 2010, pp. 19–20), and the Extended Key Indicator Method (eKIM) see (Walch, 2011, pp. 95–111). Also the European Assembly Worksheet (EAWS) enables the combined assessment of different load handling activities by summing the risk indices from different activities (Bokranz and Landau, 2012, p. 223).

For the combined assessment of different physical work stresses the tool family of the European Assembly Worksheet (EAWS), Automotive Assembly Worksheet (AAWS) and their derivatives NPW, BkB and DesignCheck (see Kugler *et al.*, 2010, p. 21) were developed for the German automotive industry. In these tools a combined value for the physical workload is calculated based on the evaluation of body postures and movements, action forces, load handling activities and, if applicable, some additional factors (Schaub *et al.*, 2012, p. 619). Repetitive activities are assessed on their own and their risk value is compared to the whole body evaluation (Bokranz and Landau, 2012, p. 230), during which the higher value is decisive for the overall evaluation .

Further, some holistic methods exist, that include other factors besides the physical workload. Popular methods include the AET, the ABA method, the BAB method and the FIOH method which are described briefly in the following section.

The „Arbeitswissenschaftliches Erhebungsverfahren zur Tätigkeitsanalyse“ (AET) procedure by (Rohmert, 1985) includes 216 items for work objects, work tools, working equipment and the physical, organizational, social and economic conditions of work (Rohmert, 1985, pp. 247–248).

With the “Anforderungs- und Belastbarkeitsanalyse” (ABA) tool 19 different influences including body postures and movements, body forces, manual material handling, environmental conditions and some organisational influences can be evaluated (Prasch, 2010, p. 47; Egbers, 2013, p. 159). This tool was developed for the German automotive industry (Walch, 2011, p. 47). Based on the different evaluation results of single tasks a weighted total ergonomic workplace score, that indicates the ergonomically representative and comparable collective value from all characteristics (Bubb, 2007, pp. 170–174).

The assessment of work-related stress (“Beurteilung arbeitsbedingter Belastungen – BAB”) procedure group includes 31 items for the activity-based assessment of combined physical stress, environmental conditions, safety aspects and psychological work stress (Gebhardt *et al.*, 2003). The results are illustrated according to the risk and the traffic light scheme in the stress documentation system (Gebhardt *et al.*, 2003). The developers state that valid assessment methods were integrated where available (Dolfen and Klußmann, 2012), and that the quality of validity and objectivity of the procedure is acceptable (Peters, 1986).

With the ergonomic workplace analysis method by the Finnish Institute of Occupational Health (FIOH) 14 items including workstation design, physical workload, lifting, working postures and movements for multiple body areas, task content and restrictions, repetitiveness, personal contact and communication, decision making, attention requirements, and environmental factors as lighting, noise and the thermal environment, as well as accident risk are evaluated (Ahonen *et al.*, 1989). The evaluation is done by an observer, who can assign a rating from 1-5 points, describe the available risk verbally for each item, and the worker, who grades the same items on a four point scale for his workstation, including the individual perception of the risk (Chiasson *et al.*, 2012, 480).

Generally, a mathematically formulation of a risk index considering manual material handling activities including different loads or body postures on screening level can be derived by a weighted combination of the individual risk factors. The risk values for the different activities have then to be calculated based on time-weighted average values. In a final step the total risk can be summed out of these values (IAD, 2010)[9].

It can be summarized that different philosophies, approaches and operationalisations exist for the ergonomic assessment of work conditions and that a multitude of tools are available for industrial application. These tools have in common that they are tailored to specific types of work activities or stress or for the evaluation of simultaneously occurring stresses. However, a need for action and changes can be formulated objectively only when based on the identification and quantification of the existing risk, and on mathematical assessment methods. If such a need for improvement has been detected, suitable remedies have to be introduced at the work place. This is done in the intervention phase of the ergonomic design process and explained in the next section

2.4.4 The ergonomic intervention process

After identifying and evaluating work stresses that cause a possible overload, an ergonomic intervention process is necessary. This ergonomic intervention process mostly targets at improving work systems through reducing stress by using the data of the ergonomic analysis (Brandl *et al.*, 2016, p. 448). Several

[9] For a detailed description of the calculation see IAD (2010).

scientific based models dealing with the development and implementation of preventive interventions are available in literature (see Holtermann *et al.*, 2010, Rivilis *et al.*, 2006 van der Beek *et al.*, 2017). Based on scientific models it can be concluded that an ergonomic intervention process should typically follow a five step approach including the phases definition of the target states (1), deriving a multitude of possible corrective measures for attaining defined target states (2), selection of a suitable corrective intervention measure (3), implementation of the chosen measure in existing work system (4) and examination of the effectiveness (5) of the implemented measure (Westgaard und Winkel 1997, S. 490). A general procedure to structure ergonomic measures and to prioritize most suitable measures is the “TOP-principle”, where the letters indicate technical (T), organizational (O) and personal (P) measures (DGUV, 2016, pp. 18–23; Schlick *et al.*, 2010, p. 744). With this structure, possible starting points for workplace improvement can be subdivided in regard to the dimension workplace, work organization, and the individual worker.

Based on this principle a hierarchy of occupational controls should follow a “STOP-approach”, where the substitution of the risk (S), as the most effective measure aims to avoid or eliminate the hazard completely was added to TOP (NIOSH, 2019). If this is not possible or feasible, ergonomic intervention concepts should primarily be of technical nature, i.e. constructive measures to minimize the risk (Berentzen and Lennartz, 2010, p. 51). If technical solutions are not possible or sufficient, in a second step, organisational measures should be introduced, i.e. spatial or temporal separation of worker and source of risk (Schlick *et al.*, 2010, p. 744). If these measures do not reduce the risk sufficiently, personal measures as personal protective equipment and behaviour related controls, as regulations on how to conduct work can be applied (BMASK, 2017a, pp. 1–2). However, these procedure does not allow to derive suitable ergonomic interventions based on workplace assessment in a structured way.

Ergonomic interventions are defined as a change process with the aim of introducing measures that influence occupational mechanical exposures and/or acute responses in order to promote musculoskeletal health. Three types of intervention are distinguished: primary intervention is aimed at minimizing occupational exposure factors (e.g., change work station design), secondary intervention is based on individual measures to lower symptoms or strengthen the resistance to harmful exposures (e.g. physical training) and tertiary prevention focuses on rehabilitation measures with a back to work design (Westgaard and Winkel, 1997, p. 494). Primary prevention measures should always be given priority (Klotter, 1998, p. 49). In practice however, secondary and behavioural measures, often represent the more cost-effective alternative and are therefore preferred. (Klotter, 1998, p. 35) The connection of the different types of interventions is illustrated in Figure 28, also showing a model of the relationship between mechanical exposure and musculoskeletal health effects.

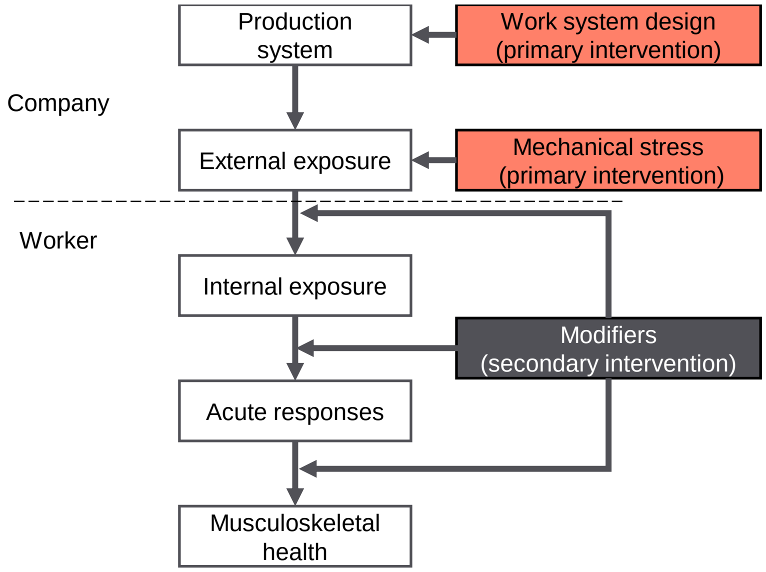


Figure 28: A model of significant issues determining occupational musculoskeletal health [adapted from Westgaard and Winkel, 1997, p. 465]

Prerequisites in terms of improving work places according to worker abilities is the structured evaluation of both characteristics. The individual abilities and skills of a worker can be recorded in the course of an occupational health examination and documented in a standardised ability profile on the basis of predefined characteristics (cf. Müglich *et al.*, 2015a) To achieve this, FCE tests can be used (see section 2.2.7).

With this tools workloads can to be recorded on process basis and classified according to predefined characteristics and the time component, similar to the ergonomic risk and load assessment, (Wittemann, 2017, p. 25). Subsequently, it is possible to compare employee skills and work requirements and discrepancies can be determined. Similarly, a fit between the intervention measure and the work task is a requirement to improve the working conditions. To assess technology profiles and evaluate them in comparison with work tasks and worker abilities, task technology fit models as used in information systems research can be utilized (cf. Goodhue and Thompson, 1995). In the following section different occupational measures for prevention of negative health outcomes are described in relation to the types of intervention.

2.4.4.1 Interventions related to work system design

In this section interventions in relation to work system design are summarized. These interventions build on rationalization strategies and health prevention management approaches.

Rationalization strategies in production system interventions

Studies dealing with rationalization strategies in production system interventions generally include a dual aim. On one hand the goal of improved musculoskeletal health and on the other hand increased productivity are the desired outputs. Critical to the intervention philosophy is that with an increasing productivity also the exposure to physical stress may increase, what complicates significant statements about health outcomes. Therefore the related studies generally provide little evidence that improved health can be achieved through redesign of the production system (Westgaard and Winkel, 1997, p. 489). However, in the redesign of work mainly primary prevention characteristics (Westgaard and Winkel, 1997, p. 466) such as the introduction of safety, health and environment (SHE) management systems and the implementation of ergonomic solutions, in terms of workplace design, work methods or job rotation, enlargement or enrichment approaches are commonly used in industry.

Introduction of safety, health and environment management systems

A goal in SHE management systems is the promotion of workers‘ health and wellbeing (ISO 45001, 2018) and as such highly relevant for dealing with workforce requirements and occupational health (Ulich and Wülser, 2015, p. 127). Typically controls in the management area include: economical aspects of ergonomic interventions, setting up target and control systems, assigning responsibilities and opening up existing structures for design and qualification opportunities, creating awareness of relevant requirements among responsible personnel, work system and work stress planning and control, as well as adapting the corporate culture (Ulich and Wülser, 2015, pp. 130–195). However, the different approaches of health-, (re)integration- and disability-management are distinguished.

Health management systems aim at the systematic and sustainable design of health-promoting structures and processes as well as the promotion of personal health improvements of employees (Badura *et al.*, 2010, p. 33). This is mostly the task of workplace health promotion programs where primary and secondary occupational preventive measures are focused (Badura *et al.*, 2010, pp. 184–185).

Occupational (re)integration management, as a part of SHE management, puts a focus on corrective work place design to reintegrate ability limited workers (Schian *et al.*, 2004, p. 71). Therefore, it can be classified as tertiary prevention measure. Corrective workplace design serves to cope with prolonged incapacity to work, to prevent renewed incapacity to work and to integrate chronically ill employees into the work process. Usually, for reintegration measures individual employee abilities are taken into account by means of profile comparison procedures when assigning a job. (Bruder, 2013a, pp. 642–644) To this end, functional capacity evaluation (FCE) tests can be used. With this tools workloads can be recorded on process basis and classified according to predefined characteristics and the time components similar to the ergonomic risk and load assessment (Wittemann, 2017, p. 25). Subsequently, it is possible to compare employee skills and work requirements and discrepancies can be determined.

Lastly, disability management deals with all types of ability limitations, performance alterations, reduced performance and deployment restrictions and aims to keep workers with limitations in employment (Schian *et al.*, 2004, p. 72). In addition, deployment limitations are often discussed in relation to the age of employees, as illustrated by the example of ISO/TR 22411 "Guidelines for standards developers to address the needs of older persons and persons with disabilities". Physical limitations, however, are often a consequence of illnesses that occur regardless of age, for example as a result of an accident.

The concept of age-management, combines such approaches and aims to maintain the work and employability of all employees throughout their working lives and combines all measures of health promotion, personnel management, work organization and work design (Kugler *et al.*, 2016, p. 439; Landau *et al.*, 2007b, p. 2; Varianou-Mikellidou *et al.*, 2019, p. 240).

Age management uses a resource-oriented understanding of employee potentials in order to generate competitive advantages (Frerichs, 2013, p. 186). The basic concept of age management is identical for all age groups, but the different age-related factors are taken into account in the design of work and the necessary adjustments and individual measures, thus depend on the age of the group under consideration (Ilmarinen, 2011, p. 26). The maintenance of the work ability is fundamental for employability, which is dependent on the worker’s health, education and competences in relation the work requirements, and thus for a productive working life until retirement (Ilmarinen, 2001, p. 549).This means that the work ability always results from the interaction between human resources and the work demands and can be improved and promoted by work-related and individual measures (Ilmarinen *et al.*, 2002b). In this context, the company plays a central role in maintaining the ability to work (Ilmarinen *et al.*, 2002b). Both, a measuring instrument for work ability, the “Work Ability Index”, and a model describing the influences on the work ability, the “House of Work Ability” were developed (Ilmarinen, 2006a; Tempel and Ilmarinen, 2013, p. 41).

The "House of Work Ability is a model describing the concept of work ability in the four dimensions health, competence, personal values, and work requirements that have to be considered in managing an ageing workforce (Ilmarinen *et al.*, 2005, pp. 5–6). The Work Ability Index is a survey tool to determine the subjective strain at work according to these dimensions (Ilmarinen, 2006a). The current ability to cope with physical and psychological stress and the current work ability is assessed by a questionnaire and the Work Ability Index provides specific indications at which level of the model requirements should be reduced or eliminated (Prasch, 2010, p. 50). However, no specific technical improvement suggestions can be derived from the work ability index (Prasch, 2010, p. 51) and the tool is mainly linked to the worker itself, instead of the working conditions to derive meaningful measures in work place design (Wittemann, 2017, p. 33). Therefore, a more specialized model on workplace level would be necessary.

An example of such a holistic management model to support worker's health and wellbeing, the so-called FIT model, was developed by Kugler *et al.* 2016. In this approach key indicators are used to provide a quick overview of the current situation (Kugler *et al.*, 2016, p. 440). These key indicators to support management decisions on three different hierarchical levels including a total of seven indicators (Kugler *et al.*, 2016, pp. 440–444). These indicators are:

- Job attendance
- Long-term illness (more than 6 weeks off work)
- A WAI (or similar index) score
- Reduced work capacity (expressed in work years or financially)
- The percentage of vacancies
- The overall score of job satisfaction
- Unplanned fluctuation in the workforce are available

Based on the indicators, measures can be derived for different groups of employees. As a result, awareness of comprehensive connections and risks is raised and the identification of risks and control measures can become more goal oriented (Kugler *et al.*, 2016, p. 439). However, also the FIT model does not offer the possibility to derive specific improvement suggestions on a workplace level.

2.4.4.2 Interventions related to the external mechanical exposure

In this section intervention in relation to mechanical stress that are summarized. Typical interventions in terms of mechanical exposure are primary prevention measures and include multiple adjustments of the work place, work methods and worker instructions. Typical design for studies assessing such interventions consist of repeated measurements of exposure and health variables on the same workers with previous and redesigned work place. Often interventions modify both, workstation design and work method, affecting all three exposure dimensions. This complicates the drawing of conclusions regarding causal relationship between workplace modifications and improved health. Overall, studies using mechanical exposure intervention measures report positive health effects following the intervention, regarding heavy manual work such as lifting. Studies in industry lead to the conclusion is feasible that a reduction in mechanical exposure can lead to a reduction in musculoskeletal symptoms, especially in jobs with a high mechanical stress level. (Westgaard and Winkel, 1997, p. 488) Typical measures extracted from different studies include the reduction of the workload or dose by means of workplace or product redesign or modifications, mechanization and the use of mechanic working aids and suitable tools, full-, or partial automation, human robot collaboration (HC) and the implementation of general ergonomic measures. (Podniece, 2007, pp. 20–21; Spillner, 2014, p. 18) If the occurrence of potentially harmful exposure cannot be avoided, the subsequent logical step is to minimise the load, the task duration, or the dose of exposure. Typical measures related to the mechanical exposure are summarized in this section.

Workplace planning and (re)design

Together, the work content and the workplace design determine the work stress. The preventive effect of interventions are mainly achieved by reducing the workload (Spillner, 2014, p. 18). A reduction in the workload in terms of loading and dose can be achieved by removing challenging tasks and combining simple partial activities into light duty workstations (Krause *et al.*, 1998, p. 115). Preventive planning approaches that consider ergonomic quality gates in early phases of the factory planning process are available in the relevant literature (overview see e.g. Spillner, 2014, p. 21). For general considerations concerning ergonomic workplace design see section 2.4.2. Compliance with general ergonomic or worker specific requirements can be achieved during workplace planning referring to guidelines and checklists for the planning process (Ilmarinen, 1992a; Prasch, 2010; REFA, 1984), or by implementing preventive load and activity limits (DGUV, 2010, p. 48; Prasch, 2010, p. 41; Bongwald *et al.*, 1995, p. 30; BMASK, 2011, p. 30; Kerschhagl and Koller, 2013, p. 30). Target-oriented design information can be obtained in form of evaluating and comparing physiological requirements of different workplace types, qualitative design specifications (e.g. avoiding static holding work), quantitative design specifications in terms of general limit values and reference values (e.g. for working height, luminance levels, load limits for handling) and by best practice examples of measures to specific types of stress, symptoms or complaint complexes from relevant literature (Spillner, 2014, p. 24).

Socio-technical work design aims to coordinate the social and technical system at work. This coordination forms the basis for human-centred work systems that promote health and learning, where the content of the design must be adapted to the specific operational tasks and the resources of the employees (Szymanski, 2016, p. 154). In relation to employee resources a focus should be put on health-based work design principles. These principles postulate that the regenerative ability and the adaptability of the employees should not be exceeded (Martin, 1994, p. 324), that work conditions should be designed flexible, so that they can be changed according to the individual abilities and skills of the employees and that they allow several strategies of action of the work execution for the employees (Martin, 1994, p. 325). Further, work should be designed in a differential and dynamic way to enable the worker to switch between different state of the art work settings for the same task (Martin, 1994, p. 325). Lastly work design should be a participatory process as the employees are regarded as the experts in their field of work and their knowledge about the work task, the work process and the working conditions are essential for a work design that optimizes the workload (Martin, 1994, p. 326).

Product and process modifications

The designed properties of the products and processes determine the later manufacturing and assembly processes and thus the work contents to be performed as well as the stresses occurring. In addition to general specifications of design for assembly (DFA) (Mital *et al.*, 2014), the early integration of ergonomic requirements can reduce or even avoid the later occurrence of stressful activities (Bierwirth, 2012, pp. 29–30). Therefore, participatory ergonomics including team building or quality circles, and the main focus on worker involvement in ergonomic solutions generation and implementation is suitable (Westgaard and Winkel, 1997, p. 487). Participatory ergonomics theories have the common element of emphasizing that workers are experts in their own job and thus are best in identifying targets for improvement. Therefore, a key for successful implementation of suitable solutions is that the improvement ideas are rooted among end users and that they are involved in the change process. (Wijk and Mathiassen, 2011, p. 366).

Mechanization and the use of working aids

Mechanisation of physical stressful activities, as well as use of aids can reduce work stress (Rademacher *et al.*, 2013, p. 247), and the energy expenditure (Shephard, 2000, p. 540). Indicators for using such measures can be derived from ergonomic analysis by means of load, bottleneck or capability analyses.

Typical examples in terms of mechanization include the application of tools as roll cages, lift trucks, gravity rollers, auto leveller, vacuum hoists, rotary tables, manually operated toggle lever presses or balancers for heavy tools etc. (Spillner, 2014, p. 27; Prasch, 2010; Hesse, 2016). An overview of available mechanical lifting aids structured by application area can be assessed (HSE, Health and Safety Executive, 2013).

Automation of heavy physical work and human robot collaboration

Automation involves a strict physical separation of man and machine and allow a separate consideration of manual workstation and automatic workstation. In this context automatic devices can serve to reduce the total load for the worker and eliminate partial loads at the workplace by transferring human work to machines (Spillner, 2014, pp. 27–28). Therefore, a possible solution for the long-term healthy employment of workers could be the automation of workstations by taking advantage of new technologies (Thun *et al.*, 2007). In classical planning procedures however, the use of automatic devices is considered primarily for economic reasons (costs, volume, quality) and not enhance ergonomics or to decrease employee stress levels (Bullinger and Ammer, 1986).

Automatic devices can also serve to reduce partial loads at the workplace by transferring defined tasks of human work to machines. It is one of the ironies of automation that human tasks require higher technical qualification (e.g. setting up, troubleshooting, programming) compared to an automated task, but with increasing level of automation the remaining non-automated tasks become even more demanding or monotonous for humans (Bainbridge, 1983). The relevance of this theory in practical application was shown by assessing work after implementing partial automation and a Chaku-Chaku assembly system in industry. Both lead to an increase in productivity and an overall decrease in the workload, however, the load or intensity of the remaining activities for the employees increased (Neumann *et al.*, 2002). Typical examples of the automation of handling processes include continuous conveyor systems such as chain conveyors or conveyor belts, or automatic handling equipment such as industrial robots e.g. for palletizing (Neumann *et al.*, 2002; Spillner, 2014).

Human-robot-collaboration can be used to avoid stressful body postures, or reduce the needed manual material handling activities (Peshkin and Colgate, 1999, pp. 340–341; Fast-Berglund *et al.*, 2016). Furthermore, adjustment and special operations can also be (partially) automated, including automatic height and reach adjustment (Rönick *et al.*, 2019a; Schlund *et al.*, 2018, p. 279) to improve posture ergonomics, or the automatic preparation and provision of relevant assembly instructions to support memory performance (Lušić *et al.*, 2016).

Through collaboration between operator and advantages of automated machinery, and assembly information guidance as well as a safe design for collaboration, the human advantages in terms of dexterity can be combined with automation (Duan *et al.*, 2012). With such a combination the operator can be supported when needed, or replaced in terms of unhealthy working conditions, so that the human operator only performs those tasks that are still executable, simpler or more appealing (Calzavara *et al.*, 2019, p. 7; Spillner, 2014, p. 80). Potential areas of robot application, include automated decoupling from cycle binding by automating subtasks, use as a hoist to reduce force requirements during handling, assembly or joining, use as a gripping aid for dangerous objects, use as a positioning aid for fine-motoric tasks, outsourcing of highly stressful tasks through (partial) automation (Spillner, 2014, pp. 80–81).

Variation of activity assignment

In order to avoid one-sided and thus potentially harmful stress, a mix is recommended that includes a change of different loads, postures and movements and psychological and cognitive demands (Buck, 2002a). Approaches that proved to be relevant in industry include job rotation, job enlargement and job enrichment methods as well as dose-response models and individual task assignment.

Job rotation is a systematic change of jobs, usually within a working group (European Commission, 2002, p. 20). Individual assignment or rearrangement of duties in terms of the activity to be performed can offer ergonomic benefits, load changes and reduction of one-sided, monotonous loads if the activities of the workplaces differ (Spillner, 2014, p. 17; Shephard, 2000, pp. 540–541). Of particular relevance for older workers is the alternation between different types of stress by rotation between several workplaces, to reduce the average time an spend on critical workplaces, that can no longer be improved by work design measures (Landau, 2009, p. 110). For a sustainable effect job rotation plans should be based on a intended load mix derived from ergonomic workplace assessment results (Walch and Günthner, 2010; Rademacher *et al.*, 2012), or on load dosimetry aiming at a reduced duration of exposures and adverse effects (Schlick *et al.*, 2013, pp. 247–248).

For individual workplace allocations and rotation on group level, job rotation strategies become an optimisation problem and are still subject to research (cf. Weichel *et al.*, 2010; Boenzi *et al.*, 2015; Jeon *et al.*, 2016; Botti *et al.*, 2017; Calzavara *et al.*, 2019). Few models have considered the ergonomic aspect of jobs together with human factors and individual capacities, in the workforce scheduling. Huang and Pan developed a model including anthropometric differences in job rotation approach to reduce the average risk and decreasing the number of workers who experience a high level of risk (Huang and Pan, 2014). Othman *et al.* developed a multi-objective model considering human factors and worker differences such as skill, fatigue, and personalities (Othman *et al.*, 2012). Azizi *et al.* presented a dynamic model for job rotation including the consideration of individual skill and the motivation level (Azizi *et al.*, 2010). Moussavi *et al.* suggested a scheduling model incorporating an ergonomic fit level of worker and workplace (Moussavi *et al.*, 2016). Costa and Miralles and Egbers as well as proposed a planning method and metrics to evaluate the efficiency of job rotation in the case of ability limited workers (Costa and Miralles, 2009; Egbers, 2013). However, new approaches will have to focus more on integrating organizational, cognitive and physical load constraints as well as individual needs and characteristics of workers including skills, functional capacities, experience levels and cognitive workload constraints (Abubakar and Wang, 2019; Calzavara *et al.*, 2019, p. 12) and age-related characteristics (DeLooze *et al.*, 2016; Calzavara *et al.*, 2019). Moreover, a focus should further be put on the need for recovery during work (Calzavara *et al.*, 2019), and the presence of supporting technologies and equipment that cooperate with humans during the work Calzavara *et al.*, 2019; Weckenborg and Spengler, 2019.

Job enlargement describes the expansion of work scope and content a similar level of qualification (Schlick *et al.*, 2010, p. 507). In this way, one-sided and monotonous stresses can be reduced (Schlick *et al.*, 2010, p. 506). This can be achieved, for example, by merging subsequent work contents and workplaces in assembly lines and can lead to an increase in productivity with lower level of worker fatigue (Kawakami *et al.*, 1999).

Job enrichment, like job enlargement, describes the expansion of the work content, but with activities of different qualification requirements (Schlick *et al.*, 2010, p. 507). The extension towards holistic work (Hacker, 2004, pp. 168–171, Ulich and Wülser, 2015, pp. 346–348), by including additional planning or organisational activities offers the employee greater autonomy and can lead to greater motivation and productivity and usually requires qualification measures for the worker (Schlick *et al.*, 2010, p. 507). A concrete example can be the extension of the job profile from an operator to a machine programmer.

Dose-response models follow the approach that the combined exposure to stress should be tracked over the course of the working life and adaptions of task allocation or workload should be based on the physical stress history (Hartmann, 2010, p. 372). Industrial examples include a study by Rademacher *et al.*, 2012 where the relationships of the dose of mechanical exposures on specific physical worker capabilities was identified to assist preventive planning. Approaches that aim to automate the documentation of physical stress in the sense of exposure dosimetry by means of automatic employee identification at the workplace

(Reinhart *et al.*, 2009, pp. 109–110), or by innovative assistance systems (Günthner *et al.*, 2014, pp. 109–110, Walch and Günthner, 2010, pp. 73–74) can facilitate the derivation of appropriate measure. Further, the recording of specific types of exposure, such as noise, by portable dosimeters is possible (Müller, 2009).

In terms of individual task assignment, profile comparison procedures can be used to compare workplace requirements and worker abilities, searching for tasks that suits the user requirements based on predefined criteria (EUOSH, 2009, p. 62; Bierwirth, 2012, p. 67; Wittemann, 2017, pp. 26–27; Landau *et al.*, 2007b, p. 133), or easy work tasks can be grouped to create light duty work places (Krause *et al.*, 1998, p. 115).

Stress based career planning

Approaches for career planning can include lifetime stress models and lifetime working time models. While stress models include a mapping of experiences, stress dose, and a planned relocation according to the experiences stress profile, working time models enable the accumulation of time credits which can be used for later working life.

In order to avoid one-sided stress, a mix is recommended that includes a change of different postures, movements and psychological and cognitive demands (Buck, 2002a). The optimisation of the concrete sequencing of different types of stress and breaks still is a subject of research (Spillner, 2014, p. 16). However, there is scientific evidence that some types of stress, can add up over time and reach critical doses (Rademacher *et al.*, 2012). Therefore, stress related workplace job registers, or heat maps can be used to for a stress related worker allocation or relocation and carer planning (Szymanski, 2016, p. 156; Matthäi and Morschhäuser, 2011, pp. 34–36).

Working time and shift work

Literature indicates that providing employees with flexibility and control over their working time is associated with positive outcomes in terms of health, well-being, increased productivity and reduced absenteeism (Tucker and Folkard, 2012, p. 33). Industrial controls include reduction of total working time, shortening of weekly working hours, part-time work, limiting the duration of shifts and flexible working hours in terms of reduction or elimination of night shifts, forward rotation of shifts, extension and distribution of shift-free intervals, avoidance of insertion shifts, rest break scheduling, enabling micro-breaks, and sabbatical years (Czeskleba *et al.*, 2012; Tucker and Folkard, 2012; Bokranz and Landau, 2012; Krenn and Vogt, 2004, pp. 53–55). The decoupling of workstations or activities at the workstation itself enables more flexible individual time management and service provision and a flexible work structuring with partially redundant or oversized systems increases the scope for individualised system timing (Prasch, 2010, p. 109). In terms of individual work time arrangements the location duration or extend of the worktime can be varied according to worker needs or individual takt or process times can be considered in planning (Costa and Miralles, 2009; Egbers, 2013, p. 46).

Examples for working time models include: working time accounts, part-time work for older employees, part-time work with wage compensation and blocked spare time (Bokranz and Landau, 2012, p. 253). They represent quasi-financial compensation, but do not contribute to prevention of health impairments (Spillner, 2014, p. 17). For the elderly worker however, lifetime working time accounts are particularly useful, because they can reduce the mental and physical stress in later employment phases of older people (Landau, 2009, p. 82). Further, flexible and shorter working times are seen as preferable measures to deal with declining overall physical capacity (Prasch, 2010, pp. 109–110). Different working time models including benefits and challenges for older workers are available in related literature (for more information see e.g. Landau, 2009, pp. 91–97).

Individual adaptions, allocation and qualification

According to the stress-strain concept individual differences in characteristics and abilities require individual workplace settings. Therefore, adapting the workplace to individual needs using a participatory intervention process is a possible measure. Further, the type and extent of the adjustments can be derived with the assistance of profile comparison procedures that enable a comparison of job requirements and employee prerequisites. A collection of several job profiles makes it possible to find suitable jobs for employees who have special needs and computer-aided procedures can simplify the process (Müglich *et al.*, 2015b). Measures for the individual redesign of the workplace include integration of lifting, standing and walking aids, machine conversions, environmental adaptations considering lighting, noise, air, and the application of personal assistance (Schlund *et al.*, 2018, pp. 281–282; Prasch, 2010, pp. 99–107).

In terms of individual workplace allocation, profile comparison procedures are used to compare workplace requirements and worker abilities, searching for a workplace that suits the user requirements based on predefined criteria (EUOSH, 2009, p. 62; Bierwirth, 2012, p. 67; Wittemann, 2017, pp. 26–27). Such profile comparison systems replace the unstructured, case-by-case assessment of the suitability of a job for a specific employee with defined criteria and queries that can be used to compare physical abilities with job requirements in an anonymous manner (Prasch, 2010). The case of individual workplace allocation for several employees can be seen as an optimisation problem and can be adapted to the company's requirements depending on the desired goal settings (e.g. smallest difference in load-ability profiles (Dubian, 2009); greatest utilisation of abilities (Egbers, 2013, pp. 84–86), smallest need for adaptation (Xu *et al.*, 2012), optimal job rotation schedules for manual assembly tasks (Boenzi *et al.*, 2015), or considering technical assistance (Weckenborg and Spengler, 2019).

Continuous qualification, and so-called lifelong or integrated learning can enable employees to have a broader range of employment opportunities including a strategic or planned change of requirements and can be considered as the basis in terms of worker reallocation due to the aforementioned strategic implications, company restructuring or the occurrence of performance limitations (Spillner, 2014, p. 16). In-house qualification, training and education can be realized by provision of complete work activities including planning, organization, execution, control tasks that are by nature conducive to learning and for personal development (Hacker and Sachse, 2014, pp. 174), or by setting up a worker qualification program. Examples for individual measures in terms of qualification include the expansion of the employee's skills in order to enable him to carry out work that requires different or higher qualifications and at the same less physical effort (Krohn and Hahn, 2000).

If no suitable job can be provided, termination or (early) retirement are remaining solutions. In this case continued employment due to the transfer to a suitable job in another working group, department or at other locations as well as in knowledge intense occupations as internal consultancy, is generally possible (Morschhäuser *et al.*, 2005, p. 166). In many jobs, workers who are affected by ill-health or functional loss might accept the options of early retirement or part-time work. To increase voluntary early retirement, measures such as establishing packages that encourage voluntary early retirement or transition to part-time work (e.g. economic benefits) can be taken (Shephard, 2000, pp. 542–543). Mandatory retirement can be attractive as a clear-cut from an administrative point of view, preventing workers to fail in annual working capacity tests. In terms of mandatory retirement, fixed limits (e.g. physical stress, or age limit) or job-related performance standards can be set as a condition of continued employment (Shephard, 2000, pp. 542–543)

2.4.4.3 Modifier interventions

Modifier interventions studies are mainly part of secondary intervention methods (Westgaard and Winkel, 1997, p. 466). Here, the aim is to adapt worker abilities to the situation at the workplace, to strengthen workers resistance to external stress, or to enhance the execution of work by introducing special break rules (Westgaard and Winkel, 1997, pp. 480–483). Modifiers can be sub-divided in direct measures like physiotherapy, physical exercise, or the adaption of work techniques and indirect measures including health education and relaxation training. Multiple measures approaches, presenting more than one modifier measure at a time are also possible (Westgaard and Winkel, 1997, pp. 487–488).

Studies examining the effects of direct measures show a significant connection of an intervention and positive health outcomes. This applies for providing physiotherapy, even though mixed results based on discrepancies due to the effects of multiple modifier interventions are reported and exercise interventions (Westgaard and Winkel, 1997, pp. 487–491). Exercise interventions can include gymnastics, strength training and aerobic training and or can be intended to influence the relationship between external and internal exposure to stress (Westgaard and Winkel, 1997, pp. 487–488) as in the case of modification of work techniques. Exercise intervention studies generally report unambiguously positive results immediately after intervention, but this is not maintained on follow-up observations (Podniece, 2007, p. 22). Studies using a low intensity exercise program, however, did not report positive results indicating that exercise interventions can improve musculoskeletal health only above a certain intensity level (Westgaard and Winkel, 1997, p. 491)

Studies examining the effects of indirect measures show a low correlation of an intervention and positive health outcomes (Westgaard and Winkel, 1997, p. 490). This can be seen in studies dealing with the effect of health education (back school, neck school, etc.) that report no significant improvement in musculoskeletal health associated with health education (Podniece, 2007, pp. 22–23), as well as in studies including relaxation training where the outcome in terms of health effects remains uncertain (Westgaard and Winkel, 1997, p. 490). Further, studies targeting the training of work technique, by using biofeedback techniques or by introducing an instruction program also reported different findings. The studies using biofeedback techniques report positive effects in terms reduction of complaints. Enhanced training in patient-handling techniques did not result in a reduction in back pain (Westgaard and Winkel, 1997, p. 491).

Multiple modifier interventions consist of health care management and/or exercise programs focusing several measures. Mostly early contact with medical staff, physiotherapy, physical exercise, education, behaviour therapy/relaxation techniques, reduced working hours and modification of work duties are preferred measures in such studies. Some studies also include personal factors and measures to select intervention programs on basis of an individual assessment. All studies report positive results in terms of improved musculoskeletal health (Westgaard and Winkel, 1997, p. 491). In conclusion, the relevant literature agrees that it is evident that modifier interventions involving the worker (medical management of workers at risk, physical training or active training in work technique, or combinations of these approaches) achieve positive results in terms of health outcomes depending on the initial level of mechanical job exposure. In contrast, more "passive" measures (health education, relaxation training) do not appear to be equally successful. (Westgaard and Winkel, 1997, p. 491)

Workplace modifier redesign

Workplace redesign in terms of modifier intervention based on the factors of the workplace assessment can be classified according to the measures tackling the external load. Generally, the risk index for all categories of work stress results from two main modifiers, namely the intensity (I) and the duration (D) of the exposure. Specific criteria considered when assessing physical work are summarized in Figure 29 and can serve to identify specific modifiers for different kind of work stress. The different measures are explained in the following sections.

	Energy turnover	Body posture	Physical forces	Manual load handling	Manual work
Intensity of load (I)	**Activity:** $R = \sum$ Working energy sales / Limit value **Lifting** (lifting height (h_2,h_1), body mass (K), gender (G), weight (L)) $WES_L=F_1*K+F_2*n*(F_3*K*(F_4-h)+F_5*L*(F_6+G)*(h_2-h_1))$ **Holding** (body mass, load weight) $WES_H=F1*K+F_2*F_3*L$ **Carrying** (speed (v), body mass (K), load weight (L)) $WES_C=F_1*K+F_2*(F_3+F_4*v^2*(K+F_5*L)+F_6*L+F_7*(K+L)*v*S)$ **Pull/Push** (path length (s), body weight (K), weight (L), rolling resistance (R), constant for pushing and pulling (S)) $WES_P/P=s*(F_1*K+R*S*L)+F_2*(L+K)$ F_i = constants **Posture:** WES determined from mean values from group assessment tables	**Posture:** R = BP*time BP = empirical value for the body position (according to EAWS evaluation) BP is defined for: • standing • walking • sitting • lying • bended / twisted BP • kneeling • squatting • working over shoulder/head • climbing	**Action forces:** **Hand Arm** $R = F_{actual} / F_{max\_Rec}$ $F_{max\_Rec} = F_{max(pp)}*P_1*P_2*T_1*T_2*T_3$ F_{max} = Static max. force $_{(PP)}$ = Force percentile P_1 = Factor for age P_2 = Factor for gender T_1 = Frequency of force exertion **Full body** $R = F_{actual} / F_{max\_Rec}$ F_{actual} = force to be applied $F_{max\_Rec} = F_{max(pp)}*P_1*P_2*T_1*T_2*T_3$ F_{max} = Static max. force $_{(PP)}$ = Force percentile P_1 = Factor for age P_2 = Factor for gender T_1 = Frequency of force exertion T_2 = Biomechanics factor for asymmetric exertion T_3 = Physiology factor for awkward positions	**Activity:** **Lifting** R = Number * (BP + weight + EC) **Holding** R = Time * BP + weight + EC) **Carrying** R = Distance * (BP + weight + EC) **Pulling/Pushing** R = distance * (BP + weight/type + EC + A) R = number * (BP + weight/type + EC + A) BP = Body posture EC = Execution conditions A = Accuracy	**Manual load handling:** **Holding** $R = Time*((F/HT)+GC+A_{pos}+WO+EC+BP)$ F/HT = Force magnitude/holding time GC = Gripping conditions A_{pos} = Arm position/movement WO = Work organization EC = Execution condition BP = Body posture **Moving** $R = Time*((F/M)+GC+A_{pos}+WO+EC+BP)$ F/M = force magnitude/ movements per minute GC = Gripping conditions A_{pos} = Arm position/movement WO = Work organization EC = Execution condition BP = Body posture
Duration (D)	**Time:** In minutes All data above in kJ/min	**Time:** Minutes/8h or % of shift	**Time:** Via frequency factor T_1	**Time:** Duration of the load defined by number, time or distance	**Time:** Time in hours/shift

Figure 29: Calculation of risk index for different physical work (see section 2.4.3)

Based on the assessment criteria the modifiers for physical work can be identified. In terms of energy expenditure (WEE) and working postures (WP) the working time and the type of activity are the determining factors. Modifier interventions can either aim for reducing the time of execution, or can aim for a reduction of the physical stress caused by the activity (e.g. switch from a squatting body posture to sitting task execution). For manual material handling (MMH) and action forces (AF), the characteristics and the weight of the load, the magnitude of force in combination with the tasks execution conditions and the body posture are the stress determining factors as summarized in Figure 30. Therefore, modifier interventions can change the characteristics of the load (seize, weight, gripping conditions), the exposure to load handling (amount, time, or distance to be covered), the body postures for load handling (adaptable workplace height, adaptable range of motion, etc.), or the conditions of work execution (ergonomic or environmental conditions, etc.).

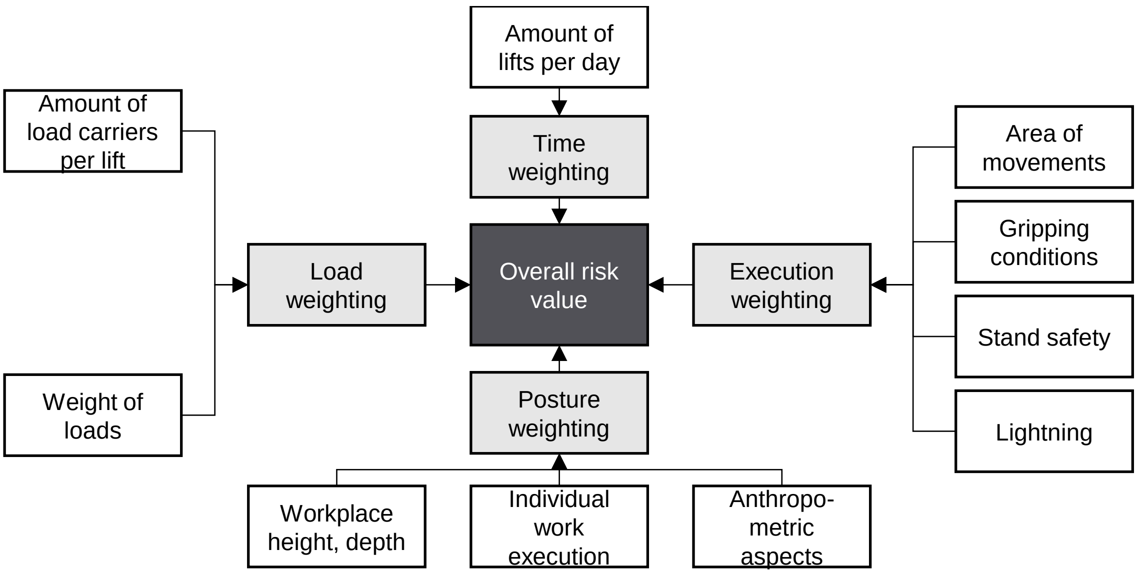


Figure 30: Elements of the risk score for manual material handling (key indicator method) that can be tackled with modifier interventions, shown at the example of a lifting activity

As shown in the figure, ergonomic measures to tackle modifiers of work execution for lifting can include the provision of smaller load carriers that increase the amount in load handling but lower the weight per lift. Also the redistribution of load manipulation to different workplaces, or the introduction of teamwork can be used to lower the amount of lifts per day and worker. By changing the design of the workplace geometry (reach envelopes, material provision, working height and area, etc.) working postures can be improved. Lastly by adapting characteristics of the work environment (sand safety, gripping conditions and climate or lighting, other execution conditions can be improved, influencing the overall stress level. (Kugler *et al.*, 2010, pp. 24–25) These modifier interventions can be used to optimize the stress caused by physical work tasks. For example, Walch developed an approach for order picking activities with minimal stress by ergonomic reallocation of goods according to their characteristics (weight, seize, etc.) to different storage places (lifting height). This approach was aimed at minimizing the ergonomic risk of material handling by allocation of products to warehouse compartments based on the overall risk score and its reduction (Walch, 2011, pp. 117–125).

Load monitoring and correction mechanisms

With regard to the physical support of employees, portable systems with integrated sensors, that record and analyse movements and loads in real time, can provide tactile feedback to help the wearer maintain an ergonomically favourable body position (Apt and Bovenschulte, 2018, p. 167). Based on real time load assessment and recording with technical devices the transparency for load doses can be improved (Römer *et al.*, 2017) and stress specific ergonomic interventions can be derived for employees (Voerman *et al.*, 2007; Römer *et al.*, 2017, p. 10). Based on physical stress and real time body data, also job rotation schedules, individual workplace reallocations can be derived for the individual employee in order to reduce the perceived work strain (Römer *et al.*, 2017, p. 12).

Division of work, by implementing working group

Work teams are small groups of interdependent individuals who share responsibility for outcomes for their organizations, including key context factors for efficient team work as organizational culture, technology and task design, mission clarity, autonomy, rewards, performance feedback, training/consultation, and physical environment (Sundstrom *et al.*, 1990). Through independent organisation and division of tasks within teams, mutual support, know-how transfer and the compensation of individual handicaps caused by changes in performance are possible (Morschhäuser *et al.*, 2005, 79, 99). However, this can result in significantly worse working conditions for healthy employees of the team, compensating for less healthy workers in their team, thus, care must be taken to balance or limit the workload (Buck *et al.*, 2002b, pp. 72–74).

For elderly workers in particular, the avoidance of one-sided work stress, positive effects on job satisfaction and performance motivation, stronger identification of employees with their work, knowledge transfer and qualification effects, and the changes and enrichment of tasks that take place are seen as benefits of working groups (Landau, 2009, pp. 117–122).

Adaption of work targets

The reduction of work targets or performance requirements by tackling workload determining parameters as such as cycle time, output targets or creation of a light workstation with the aim of reducing the work to working time ratio (Krause *et al.*, 1998, p. 118). The reduction can refer to the quantity of products and speed of execution of the activity (Kawakami *et al.*, 2000), or individual takt-, and process times (Costa and Miralles, 2009; Egbers, 2013, p. 46). This can be realized by reducing target specifications, or by slowing down takt-time or flow speed of processes (Spillner, 2014, p. 30).

Break time and break organization

To avoid fatigue, and to enable compensation (coping with stress, exercise and relaxation) an appropriate break system should be installed (WGKK *et al.*, 2004). Unstructured and self-selected breaks show a lower recovery effect than organised breaks, as they are usually taken too late, less frequently and longer than appropriate (Tucker, 2003). The introduction of short breaks reduces the amount of secondary work and thus the number of hidden or freely chosen breaks and can lead to increased performance and at the same time a reduction in stress, since work is carried out at a faster pace due to less fatigue (Dababneh *et al.*, 2001; Tucker and Folkard, 2012, pp. 25–26). Due to recovery mechanisms several short breaks are more effective than a few longer breaks of the same total length (Kim *et al.*, 2017), but there is a clear need for research concerning optimum scheduling of rest breaks (Tucker and Folkard, 2012, p. 26; Hunter and Wu, 2016)

Promotion of individual health and abilities

A goal in SHE management systems is the promotion of health (ISO 45001, 2018), operationalized by occupational health promotion (OHP). OHP is defined as a process that enables workers to increase the degree of self-determination over their health (Ulich and Wülser, 2015). The main aim can be seen in a reduction of the perceived strain by increasing health and thus the abilities needed to cope with prevalent stress. Typical measures of health promotion as part of health management include: company sports (Kenny *et al.*, 2016), regularly health checks (Schlick *et al.*, 2010, p. 133; Krause *et al.*, 1998, p. 118), physical workouts (Ulich and Wülser, 2015, p. 18; Kenny *et al.*, 2008; Shephard, 1994), back schools and exercise training and on-, or off-site physiotherapy (EUOSH, 2007, pp. 21–23; Krause *et al.*, 1998, pp. 118–119), education about healthy behaviour (Hoehne-Hückstädt *et al.*, 2007, pp. 42–50), vocational rehabilitation and training (Krause *et al.*, 1998, p. 118) as well as technology assisted digital health promotion via apps, wearables and health platforms (Niklas *et al.*, 2018, p. 75; Waldhör, 2018).

Encouraging a healthy worker lifestyle may be one of the most important asset of a work-related health promotion programme (Shephard, 2000). Therefore, also awareness for ergonomics on management level and ergonomic sensible behaviour on worker level are needed. To foster awareness on management and process engineer level tools like age simulation suites (cf. Scherf, 2014), or training in learning factories by simulating tasks and ability limitations (Wolf *et al.*, 2019) can be used. To increase ergonomic sensible behaviour at work and reduce work-related injuries and illnesses the use of real time data concerning load situation and strain reactions can be beneficial on worker level (Römer *et al.*, 2017, pp. 11–12).

Strain monitoring to derive balancing exercises

Myo-feedback training describes the use of real-time body data (e.g. physical parameters as working pulse rate, distance covered on the workday, or time spent in different body postures or the muscular activity of certain muscle groups) assessed and recorded with technical devices to give direct ergonomic feedback to employees (Voerman *et al.*, 2007; Römer *et al.*, 2017, p. 10). By the use of real time data, it is a possibility to raise the transparency of specific workplaces and workers are enabled to relate the feedback directly to their work instead of having to transfer theoretical, universal and abstract recommendations (Römer *et al.*, 2017). Further, the recorded data can be used to derive balancing or compensatory exercises, to advice a temporary change in work task to stress other muscle groups or to suggest short breaks, and similar actions (Römer *et al.*, 2017, p. 12). General balancing exercises include strengthening, stretching and mobilisation of specific muscle groups (Hoehne-Hückstädt *et al.*, 2007, pp. 49–65; WGKK *et al.*, 2004, pp. 109–128).

Information, training and instructions

General measures in terms of worker information include health information and education (back school, neck school, etc.) (Podniece, 2007, pp. 22–23), training of work technique including biofeedback techniques or by introducing an instruction program (Westgaard and Winkel, 1997, p. 491).

In health information classical tools used are paper based information sheets showing the advisable and harmful work execution techniques in terms of postures and lifting or load transportation techniques (Hoehne-Hückstädt *et al.*, 2007, pp. 25–41). Further, health education includes back, neck or posture schools, where information about general advisable behaviour information on the structure and function of the body and causes of problems are conveyed and strengthening of physical abilities can take place, aiming for enabling employees to design work processes in a way that is physically acceptable and to improve workers physical condition (Hoehne-Hückstädt *et al.*, 2007, p. 42).

Improvement of the actual work technique can be achieved by learning to apply less harmful lifting techniques and working postures (DeZwart *et al.*, 1995, p. 9), by including data based methods, that can be used to remind workers to change the execution of work, or to take a break, using sound and vibration feedback according to ergonomic or medical limits (Voerman *et al.*, 2007), or by introducing instruction programs including information and training of workers in on-site visits.

Personal technical assisting systems

A possible solution for the long-term healthy employment of workers by modifier interventions could be the use of new personal assisting technologies, which serve to reduce the workload (Schenk *et al.*, 2014, p. 619). In terms of physical assistance systems that improve workers' physical capacities different technologies are available ranging from power-assisted systems to help workers in handling overhead work (Katayama *et al.*, 2015), or collaborative robots to improve the ergonomic work situation in terms of body posture and repetitive load handling (Peshkin and Colgate, 1999; Fast-Berglund *et al.*, 2016), over the use of exoskeletons that can be used for better load distribution or cancellation of the gravity effects (unpowered/passive) or boosting strength and endurance (powered/active) of human operators (Calzavara *et al.*, 2019, p. 11), to skill-dependent automation technology that is able to support and, in some cases, replace the worker (Oba and Kakinuma, 2016; Ryosuke *et al.*, 2017)

A promising solution is robotic assistance at the workplace, where the robots collaborate with the worker aimed at reducing or eliminating high or restrictive workloads (Villani *et al.*, 2018, pp. 261–262). The robot can be used both as a collaborative and coexistent tool for the automation of subtasks. Appropriate task sharing leads to job enlargement in which the human operator only performs those tasks that are still executable, simpler or more appealing (Spillner, 2014, p. 80). In a study Spillner, 2014 generated and evaluated 60 robotic approaches of operational measures for the consideration of ability limitations (see Spillner, 2014, A8-A18). Potential areas of robot application, include (Spillner, 2014, pp. 80–81):

- Automated provision of objects in an optimal working area
- Expansion of the working area to reduce postural stress
- Reduced strain by decoupling from cycle binding by automating subtasks
- Use as of the robot a hoist to reduce force requirements during handling
- Use as a gripping aid for sensitive or difficult-to-handle objects
- Use as a positioning aid for fine-motoric tasks
- Use as a web guidance assistance and outsourcing of highly stressful tasks through automation and partial automation

Moreover, the utilization of advanced supporting technologies can provide improved working conditions (Calzavara *et al.*, 2019), and operators can receive physical support by wearing exoskeletons (DeLooze *et al.*, 2016). While passive exoskeletons support the user by providing a better load distribution and reduction of strain in specific body region (DeLooze *et al.*, 2016; Picchiotti *et al.*, 2019; Theurel and Desbrosses, 2019), active exoskeletons can serve as an amplifier for the worker's input force or torque, or to enhance precision (Dollar and Herr, 2008; Giovacchini *et al.*, 2015; Lo and Xie, 2012; Borzelli *et al.*, 2017). Further, body worn systems made from textile or lightweight hard shell material (ergo-skeletons and orthosis), can provide physical support for the worker (Apt and Bovenschulte, 2018, p. 167).

2.4.5 Implementation of preventive intervention

After choosing suitable measures, the implementation of these must be executed. Several authors have identified a total of eight different aspects of implementation and at least 23 personal, organizational, or community factors that affect one or more aspects of implementation process (Dane and Schneider, 1998; Durlak and DuPre, 2008). Meyers *et al.* analysed 25 different implementation frameworks and synthetized four general phases and 14 critical steps, as shown in Table 8. In the first phase of an implementation project, according to Meyers *et al.* the host setting has to be assessed and a decision in relation to an adaption has to be made. Thereafter, the included group of persons have to be prepared for the change. Phase two is related to the creation of a plan for the upcoming implementation. Phase three deals with the realization of the selected measure and supporting activities. Finally, phase four considers learning and documentation of the implemented intervention (see Table 8).

Table 8: Summary of the four implementation phases and 14 critical steps in the quality implementation framework (Meyers *et al.*, 2012, pp. 467–468)

Phase	Content
Phase one: Initial considerations regarding the host setting	Assessment strategies 1. Conducting a needs and resources assessment 2. Conducting a fit assessment 3. Conducting a capacity/readiness assessment Decisions about adaptation 4. Possibility for adaptation Capacity-building strategies 5. Obtaining explicit buy-in from critical stakeholders and fostering a supportive community/organizational climate 6. Building general/organizational capacity 7. Staff recruitment/maintenance 8. Effective pre-innovation staff training
Phase two: Creating a structure for implementation	Structural features for implementation 9. Creating implementation teams 10. Developing an implementation plan
Phase three: Ongoing structure once implementation begins	Ongoing implementation support strategies Technical assistance/coaching/supervision 11. Process evaluation 12. Supportive feedback mechanism
Phase four: Improving future applications	13. Learning from experience

In phase one and two management awareness, manager's attitude towards the topic and resource allocation to such projects were identified as main barriers for HSE projects. Thus, the provision of necessary resources by management and building a multidisciplinary team are prerequisites for increasing effectiveness and reduce implementation barriers. (Whysall *et al.*, 2006, pp. 813–814) In addition for the development of an implementation plan, a structured step-by-step approach is considered advantageous for the introduction and continuous use of measures that take into account workforce requirements (Sporket, 2011, pp. 293–295; Matthäi and Morschhäuser, 2011, p. 12). Furthermore, to cope with typical personal resistance to behaviour change as a main barrier for change (Whysall *et al.*, 2006, p. 811), the early information and active participation of the employees affected by the measures is considered important in order to prevent resistance or sabotage of the introduction (Zwack and Schweitzer, 2011;

Holtermann *et al.*, 2010, p. 5). Theories dealing with these, participatory approaches have the common element that workers are experts in their job and thus best able to identify a needed change (Wijk and Mathiassen, 2011, p. 366; Gravina *et al.*, 2007). Furthermore, such participatory ergonomic approaches are evaluated as very effective in relation to physical improvements (Holtermann *et al.*, 2010, p. 5).

In phase three, this is followed by the conception of new solutions, or the adaptation of known measures, as well as their application and testing in a limited (pilot) areas. However, copying measures without adapting them to the company's special requirements is mostly not effective (Brandenburg, 2009, 30-31, 64). Some measures, require regular monitoring and refreshing in order to maintain their effectiveness in long term (Ulich and Wülser, 2015, pp. 195–196). Also for the development of measures behavioural safety process theory, stresses the importance of communication and interaction for the change process to be successful and that changes can happen when workers and specialists interact (Wijk and Mathiassen, 2011, p. 366).

After testing the implementation an evaluation of benefits has to be conducted. The effect of introducing the intervention can only partly be assessed by indicators. The most part has to be measured in real world contexts (Matthäi and Morschhäuser, 2009, p. 56). Thus, rigorous experimental designs encompassing all possible influential variables as, personal, behavioural, and environmental factors are to be executed (Wijk and Mathiassen, 2011, p. 366). This makes the assessment of intervention effectiveness a challenging task. Therefore, case studies are the primary design for the evaluation of implementation processes. However, the methodological rigor and generalizability of these reports varies.(Meyers *et al.*, 2012, p. 464) Nevertheless, if suitable solutions are identified and implemented, the last step in this processes include documentation of the learning from experience (Brandenburg, 2009, p. 67).

2.4.6 Interim conclusion ergonomic workplace design

In summary, ergonomic workplace design is based on several regulations, laws and legal standards defining the minimum requirements at workplaces. Nevertheless, for human oriented work design, a higher level of adaption of the work to the worker is necessary, including aspects from the executability of tasks to the social comparability of work. To provide suitable working conditions, the first part of the ergonomic work design process is concerned with the assessment of the working conditions and a quantification of associated risks. If the evaluation results in high risk levels, an ergonomic intervention has to be carried out to improve the workplace. Generally, several measures that can reduce stress or strain are available and well documented in literature and industrial practice usually focuses on easy to implement measures from the organisation and person related domains. However, this behaviour related prevention is usually less effective and of shorter effect duration as other measures. Most potential for sustainable improvements can be identified in the primary interventions categroy, that aims to reduce or avoid the cause of overloading and do not only tackle its effects. Measures related to technical interventions show the overall highest effectiveness for stress reduction. However, in relation the individual differences in some groups of workers, the pure reduction of stress through primary interventions reaches the limit of feasibility. Thus, in relation to the group of elderly workers, a one should aim at a holistic approach, considering the experienced stress in the course of the working life, including HSE-management, a reduction of overall work stress, and modifier interventions for the control of work strain. In relation to the stronger focus on secondary prevention through technical means which is highly relevant for this group of workers, individual technical assistance is seen as a promising solution. However, for such measures a clear relation between the effects and the results of the ergonomic assessment is missing, and their implementation as well as the evaluation of their effects and benefits is a challenging task. As physical assistance by means of technologies was identified as highly relevant solution for elderly workers, the next chapter is aimed to develop a basic understanding of assistance provided by technology.

2.5 TECHNICAL ASSISTING SYSTEMS

Technological developments of recent years change the way work is conducted by the workers. Besides new challenges deriving from technological changes, also new possibilities for worker support through assisting systems arose. This section provides some background about recent developments, summarized by the collective term of “Industry 4.0”, and implications for work design. First, the term of Industry 4.0 is defined in relation to Work 4.0 and the worker. Afterwards, the theoretical background of worker assistance is discussed, stating the different types of assistance and benefits of their application for the worker. The need for physical assistance is discussed and set in relation with an ageing workforce. Subsequently assisting technologies that can provide this assistance are outlined and compared. Next, basics of technology selection in relation to specific work tasks are introduced and metrics for the evaluation of technology application benefits are discussed. Finally, the technology of exoskeletons is identified as most feasible in relation to dynamic and flexible work and the need for assistance of elderly workers. Thus, specifics of this technology are described more in detail.

2.5.1 Industry 4.0

The current phase of industrial work is often referred to as the fourth industrial revolution. After mechanization, electrification, and automation there are now several “enabler technologies” which aim to revolutionize production industry (Schumacher *et al.*, 2016, p. 15; Bischoff *et al.*, 2015, p. 24). These technologies should help factories in the future to cope with rapidly changing market demand and increasing volatility. In relation to this, Industry 4.0 describes the advancement of production and value creation systems by the combination of the physical and digital world in cyber-physical production systems (Bischoff *et al.*, 2015, p. 12). This covers multiple dimensions including technology, organization, humans, and business models (Bischoff *et al.*, 2015, p. 1). The possibilities offered by interconnected technical systems, communication, services, and humans as part of Industry 4.0 are seen as the revolutionary content (Bauernhansl, 2016, p. 454). However, strategy, organization, the smart factory, smart operations and smart products, data-driven services, and the employees are seen as the most important dimensions to consider when designing Industry 4.0 (Hammer, 2019, p. 36).

In relation to the topic at hand, the visions of the factory of the future and the work that will be conducted there by the human operators are of particular interest. The factories of the future are envisioned to be intelligently automated factories, in which machines, products, tools, workers and even customers are interconnected (Deuse *et al.*, 2015; Xu *et al.*, 2018, pp. 2947–2949). These connected sub-systems work together, exchanging information and data striving for maximum value at each process-step along the value creation chain. These smart factories are expected to enable agile production and to offer significant potential in individualized production for dynamic environments and for continuous improvement through enhanced decision making (Kagermann *et al.*, 2013, p. 19; Chen *et al.*, 2018, p. 6515). Smart operations in production are defined as a continuous exchange of information, through the integration of devices, sensors, and software, providing real-time visibility of equipment condition and operating parameters of the factory or product status (Biron, Follett 2016, p. 13). These paradigms of smart production environments and smart operations, will strongly influence the type of work conducted there and subsequently also the working tasks and the worker. These influences are considered within the paradigm of “Work 4.0” and elaborated in the subsequent section

2.5.2 Work 4.0

The work 4.0 paradigm places the operator, their ability and skills, as well as health and safety issues at the centre of considerations (Liao *et al.*, 2017, 3617, 3622; BMASK, 2017b; Horton *et al.*, 2018). Health and safety at work must be adapted in relation to the digital transformation, the demographic change, and the implementation of new technologies. To this end, it will be necessary to focus more on the psychological strain of work, alongside its physical demands. (BMASK, 2017b, pp. 135–140; Horton *et al.*, 2018, 25,33).

The working environment and required employee skills and qualifications will be significantly impacted by Industry 4.0 (World Economic Forum, 2016, pp. 20–22). Significant changes of the production processes and how industrial workers perform their jobs will be introduced with ongoing technology implementation. As a side effect, entirely new job families will be created while other will vanish (Frey and Osborne, 2017; WEF, 2018, pp. 8–9). In the past, automation has often led to inflexibility, worker deskilling and creativity loss, as well as a decreasing number of jobs (Mital and Pennathur, 2004), ending in the vision of a factory without human workers (Deuse *et al.*, 2015). Unlike in the past, when routine work was very common, oday's tasks are varied and require a quick response. Therefore, in the vision of the factory of the future the humans will have a central role as their flexibility and creativity, as well as the ability to reason and make decisions can and will not be replaced by autonomous systems (Gorecky *et al.*, 2014b, p. 294). Human presence in production systems is thus essential to compensate for technological limitations and to provide the most benefits for productivity, reliability, economy and flexibility (Mital and Pennathur, 2004). However, as a result of changing framing conditions, employees will have a higher degree of responsibility as their role changes to supervision of the strategy implementation, monitoring of the status of the system, and intervening when required (Gehrke *et al.*, 2015, p. 15). Caused by the ongoing transformation to Industry 4.0, the number of physically demanding or routine jobs will decrease, while the number of jobs requiring flexible responses, problem solving, and customization will increase also impacting skills and competencies required of industrial workers (WEF, 2018, pp. 11–12). For workers, these developments lead to an increasing work complexity, as for example the amount of information, which has to be considered in the production process steadily increases. It is further assumed that future manufacturing processes will consist of many small standardized steps which can be combined in different ways to produce different product variants (Deuse *et al.*, 2015). This also increases work complexity and the demand for information for the workforce. At the same time, for the remaining easy and monotonous tasks like machine loading or unloading the trend of increasing automation will continue. This means the workers will have a much higher share of their worktime doing complex and indirect tasks like collaborating with machines in such occupations. (Siemens, 2013) In the factories of the future one main task for workers will be observation and regulation of highly automated complex processes as well as the supervision and efficient application of machines (Frey and Osborne, 2017). Therefore, dealing with information and a large amount of data and communication with machines will be one basic element of future work tasks (Gehrke *et al.*, 2015). These technological developments will further increase the cognitive demands of the work which already contributes significantly to the perceived stress in the ageing workforce (EUOSH, 2009).

However, it is important to stress that Industry 4.0 related changes to the nature of work and the emergence of new roles, promise to benefit many workers who might otherwise confront a bleaker outlook for employment. Nevertheless, such an approach is only possible when the employees' abilities match the tasks requirements. (EUOSH, 2009) Therefore, the workers themselves need to develop a broader skillset in order to cope with the increasing complexity and have to obtain interdisciplinary knowledge. Companies will have to prepare and assist the employees during this transition by means of interdisciplinary training and qualification, and the provision of supporting technology solutions (Gorecky *et al.*, 2014a, p. 527). For the reduction of work complexity and related demands technological assistance can be provided by information and communication technology (ICT) and the rapid development and introduction of these ICT systems enable and assist the workers to play a central role (Kagermann *et al.*, 2013).

Overall, there is a consensus that technology will increase the productivity through physical and digital assistance systems that will bring about change but not the replacement of human labour. The increased use of assistance systems implies that the qualitative changes brought by Industry 4.0 will likely be positive for the workforce. Such assisted-work environments will also create opportunities for people to return to the workforce in entirely new roles if they had lost their jobs when their training and experience became obsolete (Lorenz *et al.*, 2015). Today, a structured application process for technology that assists workers and not replaces them is still missing (Jawad *et al.*, 2019).

2.5.2.1 Effects on physical work tasks

Changing market demands and new technologies also lead to several changes for industrial work systems related to a rising demand for individualized products, shorter life-cycles and different product variants (Deuse *et al.*, 2015). Therefore, highly automated mass production has to be substituted by more flexible, quicker and agile production system variants. To meet the changing customer demands, small batch size production and customization of products become increasingly important. As a result, also manual work and manually assembled products for small batch size manufacturing and logistics have regained relevance. (Wolf *et al.*, 2018, p. 68) Although the extent to which Industry 4.0, can and will replace human labour remains a matter of debate among experts (WEF, 2018, p. 16), there is universal agreement that manufacturers will increasingly use robotics and other advancements to assist workers at the remaining physically stressful work tasks. Such new technological developments have already decreased the physical work content (EUOSH, 2009). However, even though the workplace of the future will facilitate the use of a combination of exoskeletons, collaborative robots (cobots), intelligent tools, mixed reality (MR) and virtual reality (VR) solutions to support the humans (Liu *et al.*, 2019, Calzavara *et al.*, 2019), some work tasks will remain physically stressful and involve awkward postures due to limits of automation in relation to small batches, and process adjustment limits (Voilque *et al.*, 2019). The design of work situations has then to take into account new technical and organizational solutions for the changing characteristics of the future workforce (EUOSH, 2009). This way, older employees may be able to continue working longer if, for example, robotic assistance systems support them in physically demanding jobs or ICT-enabled technology provides step-by-step guidance for using new machines.

In industry tody, physical work tasks in a variety of industries are characterized by a low degree of standardization and thus a strong variation in work stress. Especially in manufacturing and logistics work the physical stress level can be significant (also see section physical work load), increasing the demand for physical assistance, particularly in connection with age-related decline of physical abilities. Most work tasks in logistics and manufacturing include manual material handling or static work and lead to physical stress in different body parts as shown in Figure 31.

○ Low
● High

		Stressed body part					
		Wrist	Arms	Neck	Shoulder	Back	Legs
Work task	Lifting and carrying	◕	◕	◔	●	●	◕
	Overhead height work	◔	◑	◔	●	◑	○
	Pushing and pulling	◔	◔	○	◔	●	◑
	Static work as drilling	◕	◑	◔	●	◑	○

Figure 31: Work tasks and physical stress for different body regions [based on (Weidner *et al.*, 2019, p. 419)

2.5.3 Worker 4.0

The mentioned limitations, mostly impact on older workers enhance the need for assistance systems to support the operator in their daily physical work (Spath, 2013). Romero *et al.* classified eight types of operators of future jobs as shown in Figure 32 (Romero *et al.*, 2016).

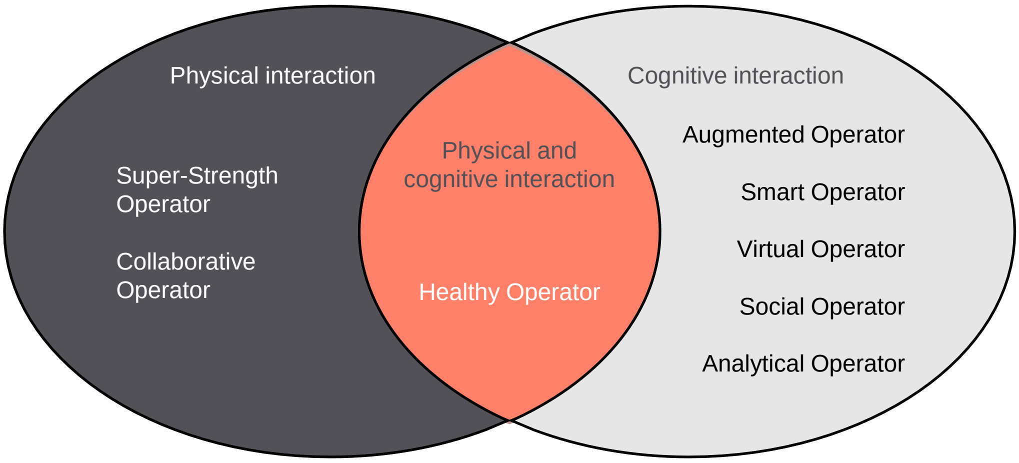


Figure 32: Terminology of the operator 4.0. An combination of physical and cognitive assistance enables the ideal condition, termed “Healthy operator” in this context (Mark *et al.*, 2019, p. 10).

For physical interactions the “Super-Strength Operator” is defined as an operator wearing supporting systems, that are flexible in terms of working area and increase the physical abilities like muscular strength (Romero *et al.*, 2016, pp. 3–4). The so-called “Collaborative Operator” is characterized by assistance for physical work via collaborative robots that can support work by task sharing or distribution (Romero *et al.*, 2016, p. 7). For cognitive interactions Romero et al 2016 define the “Augmented Operator” as a worker equipped with augmented reality (AR) devices in order to enhance the available information in real time on shop floor level with additional digital information and augmented artefacts displayed by AR headsets (Romero *et al.*, 2016, p. 4). Similar for the “Virtual Operator” virtual reality (VR) headsets can be used in computer-simulated and interactive multimedia realties, so called “digital twins” that digitally replicate a design or a manufacturing environment (Romero *et al.*, 2016, p. 5). The “Smart Operator” is supported by intelligent personal assistant (IPA) in form of artificial intelligence or a software agent for data analysis that helps the operator cooperate computers, machines, and databases (Romero *et al.*, 2016, p. 6). The “Social Operator” is assisted by social and mobile collaborative systems to be connected with several experts and the shop floor at the same time. This can support the worker by incorporating his know-how directly into the assembly-line on shop floor level and facilitate problems-solving by connecting the right people with the right information. Further, it can accelerate ideas generation for product and processes innovation (Romero *et al.*, 2016, p. 7). The “Analytical Operator” uses big data analytics tools, to observe useful information and predict events that need human attention and interaction. The big data analytics is aimed to achieve better forecasts, improve shop-floor control, enhance continuous improvement, provide visibility of relevant KPI, etc. (Romero *et al.*, 2016, p. 8)

For physical and cognitive interactions, the “Healthy Operator” is equipped with wearable trackers aimed to measure stress, heart rate, location, exercise activity, and other personal data. Wearable trackers (bio-data sensors) can drive positive change via improved productivity, well-being and proactive safety measures for the workforce. “Personal analytics” could be used to plan and schedule work-shifts, rest-breaks and overtime based on health-related metrics and individual needs. Physical and cognitive workload can be monitored during work and warnings to manage proper levels of occupational effort and stress can be provided. On workforce level this data could be used to prevent urgent threats to safety and production quality by monitoring health-related metrics and workloads and alert supervisors. (Romero *et al.*, 2016, pp. 5–6)

2.5.4 Theory and types of assistance

Assistance is a broad field of application and can take different forms. One of the main problems for the user of such systems is a too broad and unspecific offer of information and assistance, which does not sufficiently address the concrete tasks and individual needs. Further, current information and assistance systems interfere with the individual workflow and force employees to adapt their work execution to the systems used, which leads to reduced acceptance and efficiency of use. (Schlund *et al.*, 2018, p. 283) Based on an extensive literature search the criteria for differentiation of assistance can be named as area, scope/level, frequency, goal, the coupling of human and technology and adjustment/adaptability of support[10].

In terms of **adaptability** a differentiation can be made in static or dynamic information provision or assistance. While static describes the state without adaptability, dynamic support can be differed in relation to the type of customizability, which can be adaptable by the user, or adaptive in terms of self-adapting to user needs (Wandke, 2005, pp. 146–147; Schlund *et al.*, 2018, p. 283). Further criteria that allow variation are the type of information provision (paper, screen, glasses, projection, etc.), the design and layout of information provision, (software ergonomics), the scope and granularity of information, the interaction modalities (input/output), and the competence and support levels of users (Schlund *et al.*, 2018, p. 283). In relation to the **coupling of human and technology** a differentiation can be made as well. Assistance systems can be separate from the user, surrounding, close to the body, body-worn or implanted (Karafillidis and Weidner, 2016, p. 242). According to the **frequency,** support can be located in the continuum from single use to permanent assistance (Schlund *et al.*, 2018, p. 283). The difference can be classified in relation to time, whereas the usage of the assistance can be detailed as unique for example in initial training, temporary or selective for specific tasks or stresses, periodical for example in relation to a job rotation schedule, or permanent (Niehaus, 2017, p. 9). A further distinction can be made according to the **scope of support** can vary from partial to full assistance. The differentiation can be made in relation to the degree of assistance from low to high support Further, an individual degree of support can be achieved with a variable or adaptive scope of support. (Apt *et al.*, 2018, p. 19)

The **goal of assistance** can be divided into human-centred goals as ability extension, maintenance of skills or prevention of health risks. Thus the assistance can be performance increase, health maintenance or reduction of physical and mental strain (Apt *et al.*, 2018, p. 19; Mark *et al.*, 2019, p. 10). Further, an aim of assistance can be to enable the inclusion of persons with special abilities into work (Schenk *et al.*, 2014, p. 619; Mark *et al.*, 2019, p. 11). The **area of support** can be divided according to different criteria as the human functions supported (physical, cognitive/psychological, organizational, social/communicative), the body region supported, or the type of relief provided. In relation to the supported functions several taxonomies are available that differ slightly in the included content. Timpe defined human functions to be supported by assistance systems and specified eight general functions to be included. In this taxonomy the perception (1), the sensory-motor functions (2), the motivation (3), learning (4), thinking (5), problem solving (6), decision making (7) and language (8) are defined as areas of possible support (Timpe, 1998). Wandke suggested a similar taxonomy for assistance but instead of focusing on human functions the six action stages motivation, activation and goal setting (1), perception (2), information integration and

[10] Cf. Schlund *et al.* (2018); Mark *et al.* (2019); Karafillidis and Weidner (2016); Weidner *et al.* (2019); Weidner *et al.* (2013); Weidner and Karafillidis (2015); Apt and Bovenschulte (2018); Niehaus (2017); Reinhart (2017a); Reinhart *et al.* (2017b); Weidner *et al.* (2016b).

generation of situation awareness (3), decision making and action selection (4), action execution (5) and processing feedback of action results (6) are used for the taxonomy (Wandke, 2005, p. 136). Further, general types of functions of support as a coach-, display-, translation-, or filter assistance, power amplifier, or feedback assistant were defined and described (Wandke, 2005, pp. 136–145). Helms summarized the action stages in the function clusters of information integration (sensory assistance), information processing (informational assistance), and information execution (actuatoric assistance) in relation to the industrial assisting robots (Helms, 2007, p. 23).

A structured differentiation according to the type of relief was suggested by Weidner *et al.*, who specified four different types of relieve that can be physical, psychological, organizational, and social. In the physical domain, support can be provided for force redirection and induction, force enhancement, stabilization, bracing, precision or ergonomic improvement. In the psychological domain systems can provide enhanced work instructions, monitoring of the activity or of musculoskeletal stress and strain, they can facilitate the compensation of feelings, time management, distribution of activities, and job security. In the organizational and process-oriented relief domain assistance includes working instructions, suggestions and improvements as well as the monitoring of processes, and the definition of work sequences and system states. Finally, in the social area relief can be provided when the support assists the coupling of people and the flow of communication, when a (re-)distribution of activities is possible, or when unavoidable hierarchical or professional differences can be minimized. (Weidner *et al.*, 2016b)

A specification of types of support according to industrial work with respect to age-related changes of human abilities was introduced by Wolf *et al.*, 2016 and Wolf *et al.*, 2018 as shown in Figure 33. There the assistance was classified according to physical work, cognitive work tasks and collaboration and cooperation activities that combine organizational and social relief (Wolf *et al.*, 2018, pp. 73–74).

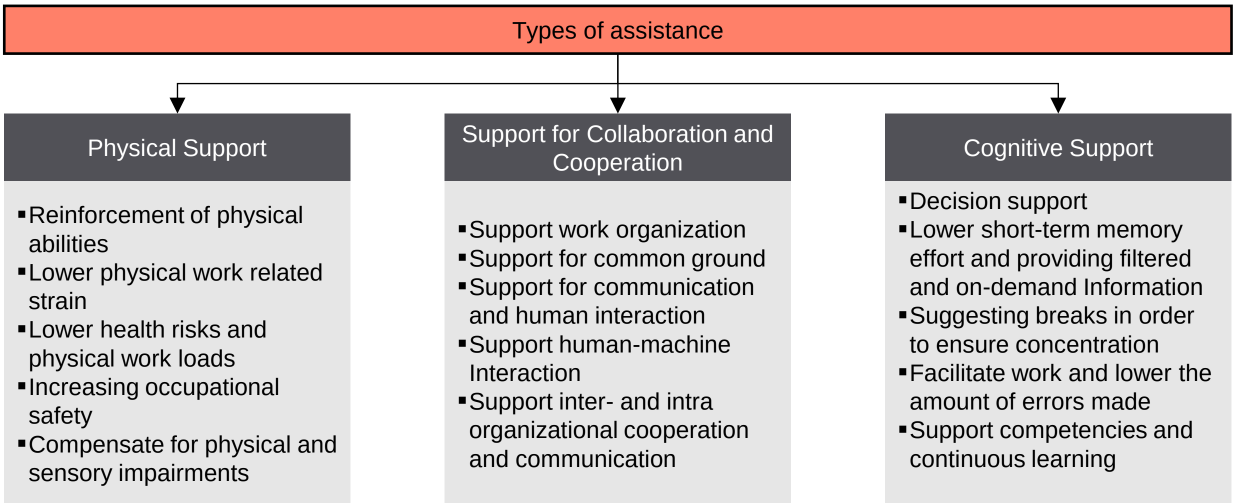


Figure 33: Types of industrial assistance aimed at elderly workers (Wolf *et al.*, 2016)

In accordance with the needs of the specific group of workers, support for physical work in industrial settings can address the reinforcement of physical abilities like strength or fine-motoric skills and lower physical work related strain by the use of exoskeletons, positioning devices, robots or automation of monotonous tasks. Further, the adaption of tools and work places to different body sizes and movement areas and impaired abilities to move parts of the body can be supported and health risks can be minimized by lower physical under- or overload through monitoring of body data, or the dose of hazardous substances. Occupational safety can be increased by improving work ergonomics and avoiding risks in human-machine-interaction for example though recognizing the human action-intension, or through the adaption of signals and warning signs to workers' physical characteristics, in particular to hearing or visual, or other sensory impairment. (Wolf *et al.*, 2018, p. 74)

Support for collaboration and cooperation in industrial settings is necessary due to the fact that people need to communicate, to organize work (scheduling, planning, distribution of tasks, monitoring of tasks and results of work, etc.), and to ensure a common ground (e.g. standard work processes, best practices, joint vocabulary, etc.). The topic of assistance for collaboration and cooperation is addressed in the field of research, called computer supported cooperative work (CSCW) that deals with the support that ICT can give to tasks as communication, work organization, common ground work and the special needs related to elderly workforce. (Wolf *et al.*, 2018, p. 74)

As industrial work becomes more knowledge intensive, support for cognitive work becomes highly relevant in manufacturing industry. In support for cognitive work it is aimed to find an optimal distribution of work between men and machine. For instance, there are a variety of tasks that humans can do, but computers may be better at, such as looking for a specific, pre-defined pattern in a large database. Concrete examples for functionalities that extend or support humans in cognitive work include the visualization of alternative decisions that take into account human information processing in order to reduce biases in decision-making, lowered requirements in short-term memory effort by visualizing detailed on-demand information, suggesting breaks, in order to ensure concentration based on age profiles or monitored physiological signals. Further, by providing assistance the amount of errors made can be lowered on the shop floor by real-time observation of the process and by the provision of skill-based work instructions. Lastly assistance systems can support continuous professional training and learning. (Wolf *et al.*, 2018, p. 75)

On a more specific level for physical assistance systems a differentiation is often available in relation to the body parts that are assisted by the technology. Especially in the area of exoskeletons it is very common to relate assisting functions of the technology to the body parts that are assisted (Weidner *et al.*, 2019, p. 424; Voilque *et al.*, 2019, p. 16). Also a differentiation can be made according to the main area of application taking into account the areas (e.g. logistics, service, assembly, manufacturing, training, etc.) where they have proven to be useful (Kasselmann and Willeke, 2014, p. 11; Niehaus, 2017, p. 9). Lastly a differentiation is possible according to the mode of action. A support system can either be passive (mechanic solution), active (electrified solution with actuators) or semi active what describes a combination of the aforementioned systems. Active systems are usually performance or ability enforcing while passive systems support the distribution of stress in the body (Hensel *et al.*, 2018; Wandke, 2005, pp. 147–148).

Based on the literature discussion a basic morphology for assistance is summarized in Table 9. The summary of taxonomic criteria and their characteristics based on scientific literature, can help to clarify different types of assistance and can be used as a basic framework for the identification of suitable systems in relation to work specific demands.

However, as outlined in the section, there are several factors that can help to differentiate assistance systems, but a clear connection of assisting functions to work related stress and strain is still missing in this field of research (Schlund *et al.*, 2018, p. 283). Further, a clear procedure to relate the main functions of assistance systems to task specific requirements is currently not available in literature.

Table 9: Dimensions of assistance possibilities

Criteria	Dimension					Source
Adaptability	static	dynamic	adaptable	adaptive		Wandke, 2005; Schlund *et al.*, 2018
Coupling	separated	surrounding	close to the body	body-worn	implanted	Karafillidis and Weidner, 2016
Frequency	unique	temporary	selective	periodical	permanent	Niehaus, 2017
Scope	low	medium	high	variable		Apt and Bovenschulte, 2018
Goal	ability / performance extension	ability/ performance maintenance (preventive)	reduction of physical and mental strain (reactive)	inclusion (compensatory / inclusive)		Apt and Bovenschulte, 2018
Performance	control	support	reduce stress and strain	inform	advise or instruct	Niehaus, 2017
Area of support	physical	cognitive / psychological	organizational	social/communicative		(Weidner *et al.*, 2016b)
	physical / sensory	cognitive	cooperation and collaboration			Wolf *et al.*, 2018
Task	perception / information intake	decide / information processing	execute / information execution			Reinhart *et al.*, 2017b; Helms, 2007
Type of relief	physical	psychological	organizational	social		(Weidner *et al.*, 2016b)
Area of application	logistics	maintenance	manufacturing	assembly	service and learning	Niehaus, 2017; Kasselmann and Willeke, 2014

2.5.5 Possible impacts of assisting systems

According to Slack *et al.*, 2016 performance measures can be conducted at three levels: society, strategy, and operations (see Figure 34). On society level effects on people, profit and environmental sustainability have to be considered. On strategic level plans for risk management, capital utilization, revenue and costs as well as the capability for innovation need to be considered. On operations level the performance of the execution of daily business is the major concern. To evaluate operational performance general key performance indicators (KPI's) include the factors quality, speed, dependability, flexibility and cost (Slack *et al.*, 2016, pp. 261–262).

Process technology is defined as machines, equipment, and devices that create and/or deliver products and services, and range from material processing (production), over information processing (IT) to customer processing (service) technologies (Slack *et al.*, 2016, p. 247). Material processing technologies include technology that transforms, transports, stores, or changes physical objects. Information processing technologies is a summary term for any device which collects, manipulates, stores or distributes information an customer processing technology describes all technologies that enable to consummation of a service for the customer (Slack *et al.*, 2016, p. 249). Generally, assisting systems can be allocated to material (physical) and information (cognitive) processing technology and have effects at the societal level (employee satisfaction and health and safety issues), and on operational level (different KPIs as quality, speed and cost).

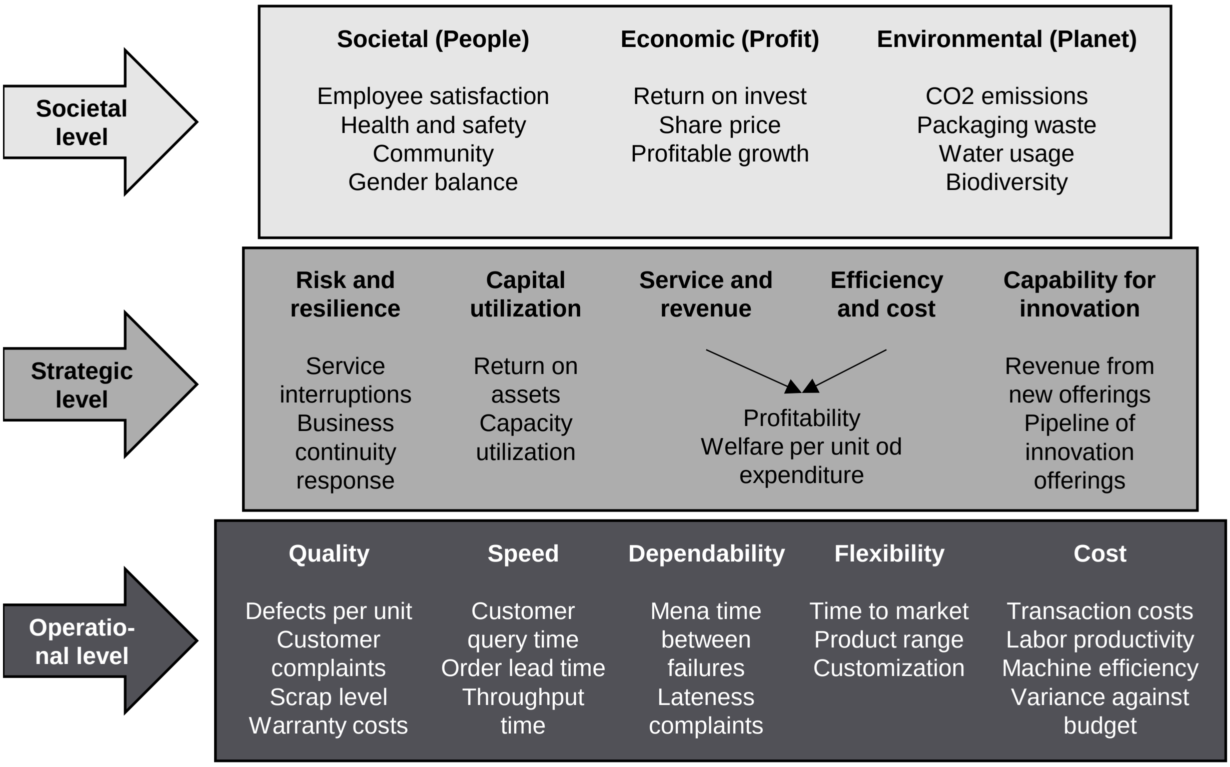


Figure 34: Performance measures at the three levels (Slack *et al.*, 2016, p. 64)

On the societal level an impact on employee satisfaction and health and safety can be assumed when the assisting system meets the workplace and worker requirements. Therefore, a match between task and technology is necessary. Thun *et al.*, 2007, Spillner, 2014 and Barrios and Reyes, 2015 stated that a possible solution for long-term healthy employment could be the automation of workstations by taking advantage of new technologies. In terms of new technologies, especially physical assistance systems are seen as an promising solution to reduce the workload in this context (Schenk *et al.*, 2014, p. 619), however, the impact on the physiology is not fully understood and is an ongoing topic of investigation (Spada *et al.*, 2018). The majority of the conducted studies that focus on industrial applications of physical assisting technology investigate the impact on muscle activation measured with electromyography (EMG) of distinct muscle groups (DeLooze *et al.*, 2016). Fewer studies extend the EMG measure by several other tests as heart rate, postural balance and perceived exertion (cf. Theurel *et al.*, 2018). However, there remains a lack of scientifically grounded findings on the biomechanical effectiveness of physical assisting systems, and a lack of research results on possible negative long-term consequences as a result of possible load redistribution or unexpected additional loads (Hensel and Steinhilber, 2018, p. 108)

On operational level process technology has a very significant effect on standard operations KPIs as quality, speed, dependability, flexibility and cost (Slack *et al.*, 2016, pp. 247–248). Only a few studies on outcomes of assisting systems on operational KIPs are available, but it is evident from literature that cognitive and physical assistance can positively impact on different KPIs as productivity (OEE), flexibility speed/time and quality (Hinrichsen and Bendzioch, 2019; Keller *et al.*, 2019; Dahmen *et al.*, 2018a, p. 1279; Butler and Gillette, 2019; Nöhring *et al.*, 2018). Considering costs, the three most significant types of costs and benefits of occupational health and safety are identified as follows. Costs derive from safety-related care and occupational health care, investment in measures and general organisational costs. Benefits emerge through added value, through a better image, added value through increased employee motivation, and satisfaction and cost savings through avoided operational disruptions (Bräunig and Kohstall, 2013, p. 12). Even though the return on investment in human centred work design and health-promoting work structures can hardly be measured in the short term (Schleicher *et al.*, 2010, p. 10), a few studies examined the ROI of preventive measures based on scientific methodological approaches. Long and short term ROI in health and safety have been reported to be economically beneficial for companies with coefficients between 1,445 and 2.2 (Bräunig and Kohstall, 2013, pp. 29–32; Zana *et al.*, 2019, p. 408).

When assessing assistance systems as part of process technologies three important areas have to be evaluated. First, the matching between technology and the task should be considered, then, second, the improvement of operations performance is of interest and third, the financial return of the new technology has to be acceptable (Slack *et al.*, 2016, p. 258). Every holistic approach to evaluate the impact of any process technology on an operation has to assess how it affects the execution of work, the influence on productivity and its economic feasibility.

2.5.6 Assisting technologies

In terms of different supporting systems, a similar conclusion as for the types of assistance can be drawn. There are several systems for different applications at the market, but the development of these systems was barely linked to work task requirements or the needed assistance (Schlund *et al.*, 2018, p. 283). Scientific works in relation to worker abilities and work requirements as well as to a derived need for assistance are summarized in the following section.

2.5.6.1 Technology for cognitive assistance

Cognitive assistive systems support manual tasks by providing instructions or warnings. People perform the tasks independently and are informed in case the system detects deviations (Weidner *et al.*, 2016b, p. 570). In terms of assistance for cognitive abilities several measures have been suggested as well. Augmented reality (AR) devices can support workers in remembering information, procedures and the correct tool setting during production, thus improving productivity and minimising idle times (Yuan *et al.*, 2008 Lee *et al.*, 2017; Yuan *et al.*, 2008; Ong *et al.*, 2008). AR assistance can be used to display visual instructions in order to provide support for maintenance and repair tasks, product assembly, quality control (Calzavara *et al.*, 2019, p. 8). Moreover, augmented reality can be applied for virtual training and knowledge transport as well as the recording, processing and dissemination of different specialist and empirical knowledge within the company with the help of cross-generational cooperation, teaching and learning (Apt and Bovenschulte, 2018, p. 167). Practical examples for AR applications were shown by Apt *et al.*, who described several AR applications with glasses and projection based systems for machinery repair, assembly and order picking activities (Apt *et al.*, 2018, pp. 46–90). Intelligent smart tooling can assist with step-by-step worker guidance, including the correct calibration of the tool for the current task. Further, the operations carried out by the operator can be monitored and recorded to ensure quality control and eliminate manual logging (Takahashi *et al.*, 2016; Gorecky *et al.*, 2014a). Finally, cognitive assistance can help to improve the working condition in general by the use of new tools and software models for simulating the manufacturing process and obtaining a precise ergonomic analysis before building a prototype (Del Fabbro and Santarossa, 2016; Ngo *et al.*, 2016). The virtual environments can represent one or more configurations of products or the work places while the operator can try each of these configurations, virtually performing all the activities without being at risk or needing a physical prototype of the product or workstation (Wu *et al.*, 2012). Further, wearable sensor devices can aid in occupational risk assessment providing several advantages in comparison to current assessment methods, as shown in a recent literature review by Alberto (Alberto *et al.*, 2018).

2.5.6.2 Technology for physical assistance

The purpose of physical assistance systems is to reduce physical strain by improving force diversion, force application, force amplification, stabilization, support work execution and improve ergonomics (Schlund *et al.*, 2018, p. 279). In terms of systems that improve physical capacities, different technologies were suggested ranging from collaborative robots and lifting aids or balancers, over exoskeletons, to skill-dependent automation technology (Weidner *et al.*, 2016b, p. 570).

Robots are used for human-machine-cooperation based on the main idea to divide the desired activity into sub-activities that are either carried out by the human or the machine at a shared workspace (Krüger *et al.*, 2009). The concept of collaborative robotics is used to improve the ergonomics of work situation in terms of body posture and repetitive load handling (Peshkin and Colgate, 1999; Fast-Berglund *et al.*, 2016). In general, cobots can be used to minimise work-related health risks from physical and/or mental overload by performing activities of high physical intensity, duration and frequency or mentally monotonous activities, which is the main, or at least a partial, goal for cobot application (Mühlmeyer *et al.*, 2019, p. 2, Weidner *et al.*, 2016b, p. 570). Collaborative robots are especially supportive for small lot seize production of individual variants. Therefore, simple and repetitive tasks within a restricted work area can be executed by the cobots. While low operating costs and high endurance are seen as advantages of collaborative or automated robotic systems, high investment costs, low flexibility and low adaptability are main disadvantages (Weidner *et al.*, 2013, p. 675)

Traditionally, lifting aids as assistance systems support the manual handling of loads and allow loads to be lifted, carried and transferred without forces acting on the human body. Special types of lifting aids are balancer used for the transportation of the work piece and tele manipulators applicable for separating the operator for the source of risk in cases of dangerous environments or inaccessible areas (Weidner *et al.*, 2013, p. 675). these mainly stationary systems provide optimal physical support, but suffer major disadvantages from its location dependency, flexibility restriction, restrictions of freedom of movement, time delays and increased movement effort (Hölzel *et al.*, 2015, pp. 149–150; Bornmann *et al.*, 2016, p. 508).

To reduce flexibility and time disadvantages portable support structures (exoskeletons) were developed. Exoskeletons can either be active (actuated) or passive (mechanic). Active exoskeletons increase the force, mobility or endurance of workers (Weidner *et al.*, 2016b, p. 570). Such systems can be limited to individual body part support or can provide whole body support (Borzelli *et al.*, 2017; Noh *et al.*, 2016; Katayama *et al.*, 2015). Passive systems have their main applications area in improving load distribution in the body and the reduction of stress in specific body regions (DeLooze *et al.*, 2016; Picchiotti *et al.*, 2019; Theurel and Desbrosses, 2019). The performance of exoskeletons to reduce work-related MSDs is estimated to be high, and the major advantage of such systems are the high flexibility of use due to adaptable body worn system design (Bornmann *et al.*, 2016, p. 509). Disadvantages of wearable systems are in general that the forces absorbed must be transferred to other body parts (Hölzel *et al.*, 2015, p. 150), and discomfort at the contact point between user and technology (Motmans *et al.*, 2019).

According to the work stress deriving from physical work tasks, physical assistance systems can serve to reduce strain and therefore, health risks. Weidner *et al*. 2016 compared different systems according to several criteria as shown in Table 10. In their analysis, classical manual workplaces, industrial robots, cobots, lifting aids, exoskeletons and information assistance systems were included (Weidner *et al.*, 2016b, p. 571).

Table 10: Comparison and characterization of physical assistance systems [based on (Weidner *et al.*, 2016b, p. 571) and (Weidner *et al.*, 2013, p. 680)]

Character-istic	Approach						
	Human	Robotic		Lifting aids		Body-worn	Information
	Manual workplace	Robots and automats	Cobots	Tele-manipulators	Balancers	Exoskeletons	Assisting systems
Performing tasks	human	machine	cooperation of human and machine	human controls machine	human handles machine	human is supported by the machine	human is informed by the machine
System boundary	combined	separated	combined	separated	separated	hybrid	combined or hybrid
Design	user individual and process oriented	process oriented	process oriented	process oriented	process oriented	user individual	process oriented sometimes user oriented
Flexibility	adaptable to product and operator	low product variance and simple tasks	product variance limited by tools; user independent	product variance limited by tools and kinematics	product variance limited by tools;	no limits for product variance; adaptable to operator	adaptable to product and operator
Lot seize	low to medium	medium to high	low to medium	low	low to medium	low	low to high
Support	hand tools	automation taking over activities	taking over some load; increased ergonomics	hazard avoidance; increased accessibility	guiding and carrying support	support of force, endurance, mobility	assist predefined functions
System configuration	usually fixed but easily adaptable	usually fixed and not modular	usually fixed and not modular	sometimes individual parameteri-zation	no possibility for adjustments	fixed; usually individual parameteri-zation	usually fixed and not modular
Development	fully developed	fully developed	fully developed; new procedures	partially developed	fully developed	low-medium maturity for industrial application	several systems fully or partly developed

2.5.7 Task-technology fit

As mentioned before there are several different technology clusters and a multitude of technologies that can support workers in different ways. The common thing about all these assistance systems is that they are not sufficiently linked to work related problems of the intended operators. As described in the previous section, literature reports very specific about stress reduction in different body parts or specific muscles, which only provides a low level of information for actual practical application of such measures. For a successful use case classification in industry a link of work place related stress and assisting capabilities of a technology has to be established. The process engineer responsible for workplace improvements usually knows the workplaces very well and can estimate the related stress, ergonomic risks, or physical complaints deriving from it. Further, information about functionalities of assisting systems and how a reduction of e.g. biceps muscle activity might improve work conditions for the workers are, however, usually not available in industry. This is further complicated by the fact that in scientific literature a low level of knowledge considering the match of physical preventive measures, especially in terms of assistance systems and work stress or a reduction of physical ergonomic risk factors, is available. While for information technology task-technology-fit models were developed and testes (cf. Goodhue and Thompson, 1995), no such models are available for physical assistance systems. Further, the motivation of support may be different for each case, either as compensation of ability-requirement gaps or for the compensation of increased requirements caused by customization of products, increased demands on quality or global trends such as globalized markets, technological changes, or the demographic development (Weidner *et al.*, 2016b, p. 572).

All this considered, the implementation of physical assisting technology is a complex challenge comprising multiple factors such as the technology, the worker, and the work task. Within the work task context, the suitability of a technology has to be considered as some tasks are best suitable for human operators, some for automation technology, some for human robot collaboration and some for exoskeleton technology. This highly depends on work task determining factors as the load characteristics (shape, size, weight) and workspace features (volume, variants, access). Within human context musculoskeletal condition, psychomotor skills and technological self-efficacy have to considered. Important factors in the decision making process are shown in Figure 35.

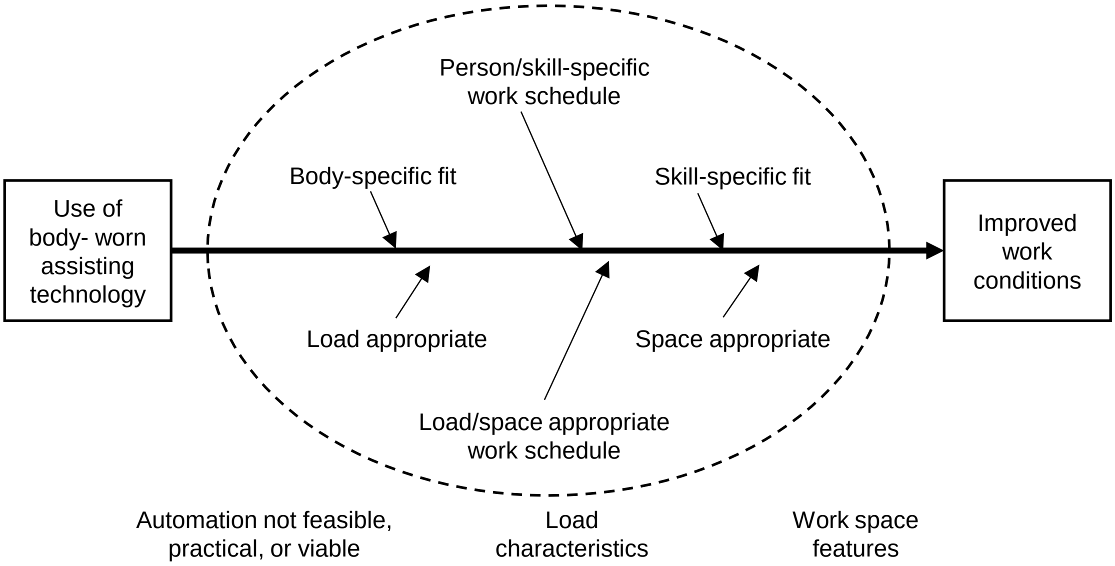


Figure 35: Multiple factors required to enable successful implementation (Fox *et al.*, 2019, p. 800)

Therefore, the selection of a suitable devices should be based on a body-, skill-, load-, and space specific fit of task, technology and operator (Fox *et al.*, 2019, p. 800). But, contrary to that, the current selection of suitable measures is mostly conducted on a subjective base, depending on the specific workplace and worker, consuming a high amount of resources per case and being often not transferrable to other cases. To overcome these limitations, the decision process should be scientifically founded, objective, process-driven and flexible (Dahmen *et al.*, 2018b, p. 269).

To derive suitable solutions based on a structured approach a worker-workplace-technology fit design for physical assistance is missing. In a structured methodical approach, the need for assistance has to be derived based on workplace and work task requirement assessments and a comparison with workforce abilities and limitations must be conducted. In a second step, this need for assistance can be compared to assisting functions provided by suitable measures. Basic approaches available are summarized in the following section.

2.5.8 Selection of suitable technologies

A scientific model describing the use of assistive technology device (ATD) is the "Framework for the conceptual modelling of assistive technology device outcomes" (Scherer *et al.*, 2007, p. 4). In this model the interaction among characteristics of a specific device-type, its users, and their environment are considered to describe outcomes on continuing or discontinuing use of an ATD. It is intended to identify features that are associated with positive outcomes and provide testable predictions about user benefits from devices. Continued use can only be achieved if short and long-term benefits in terms of productivity a perceived utility exist. The perceived utility is strongly moderated by different co-factors as the factors described in the ICT framework, other interventions, health issues, or costs as illustrated in Figure 36. (Fuhrer *et al.*, 2003).

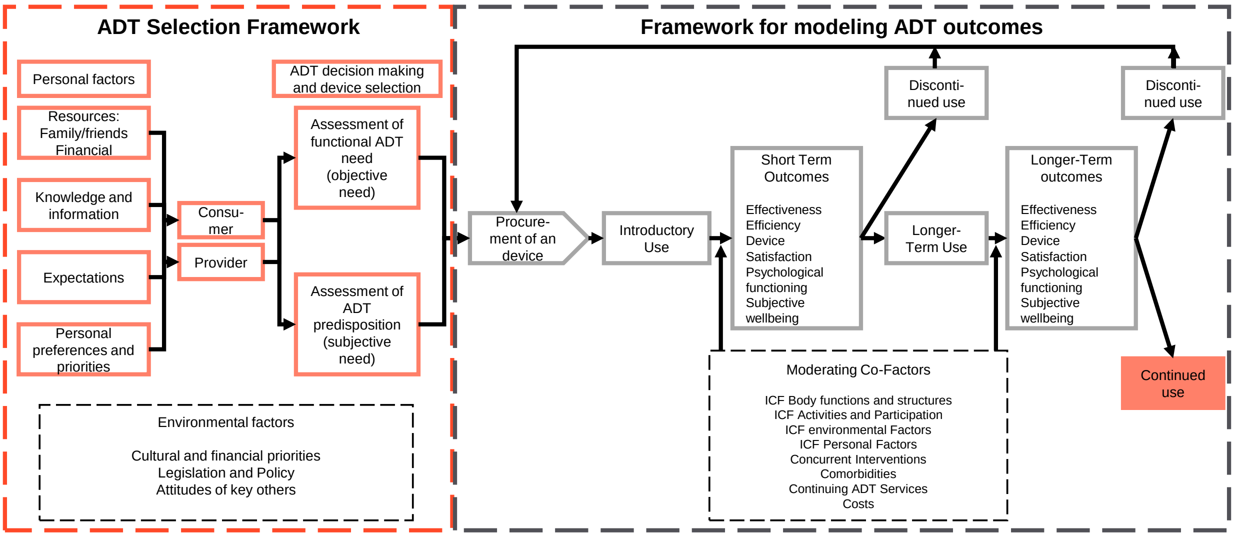


Figure 36: A framework for selecting and modelling the outcomes of assistive technology devices (Scherer *et al.*, 2007, p. 4)

The framework for modelling ADT outcomes was extended aiming to derive a fit between humans, environment and assistive devices. The model to identify suitable assistive devices is named the "ADT selection framework". In this model the ADT consumer and provider with their influencing personal factors are seen as the key factor for decision making. The resources and knowledge, expectations as well as, personal preferences and priorities, define the person's predisposition to the use of a particular ATD (Scherer *et al.*, 2007, p. 6). Further, the decision is determined simultaneously by both, the objective and subjective need for assistance. While the objective need for assistance derives from physical impairment and limitations, the subjective need is linked to individuals predisposition to overcome participation restrictions, (Fuhrer *et al.*, 2003, p. 1245). Further, it should be noted that the subjective and objective (functional deficits) need for assistance often do not match (Fuhrer *et al.*, 2003, p. 1246). Therefore, a positive outcome of the decision-making, is an individualized or individualizable intervention that considers the unique individual characteristics, with a low complexity that is coupled with strategies for ongoing use as well as for the assessment of the possible change in assistance needs (Scherer *et al.*, 2007, p. 7).

Even though the ADT selection and outcome frameworks were mainly developed for application in rehabilitation and for severe health impairments, the selection process and the framework to describe outcomes of usage can be easily transferred to assisting systems for industrial use. Therefore, the model builds a scientific base for the application of support systems in industrial environments. The important learnings from this model include the difference in subjective and objective need for assistance and the inclusion of short-term and long-term benefits in terms of productivity and perceived usefulness as predictors for continued use of the device. Because of its roots in rehabilitation science the model does not provide more detailed information about the objective physical need for assistance in industrial settings, based on different work tasks. Therefore, models at a more detailed levels are necessary.

Need for assistance

The general need for assistance can be understood as the discrepancy between the skills offered by the workforce and the requirements of work tasks. In terms of the available skillset, the International Classification of Functioning (ICF), Disability and Health can be used to structure normal worker abilities. The model describes individuals in terms of level of functioning, rather than describing levels of deficit or disfunctioning (ICF; World Health Organization, 2001). Its purpose is to provide a framework for assessment, diagnosis, intervention and outcomes measurement, regardless of health or ability. Individuals are described in terms of their health condition that is the result of six influencing factors, the body function and structure, activity, participation, and contextual factors (environment and personal) as illustrated in Figure 37.

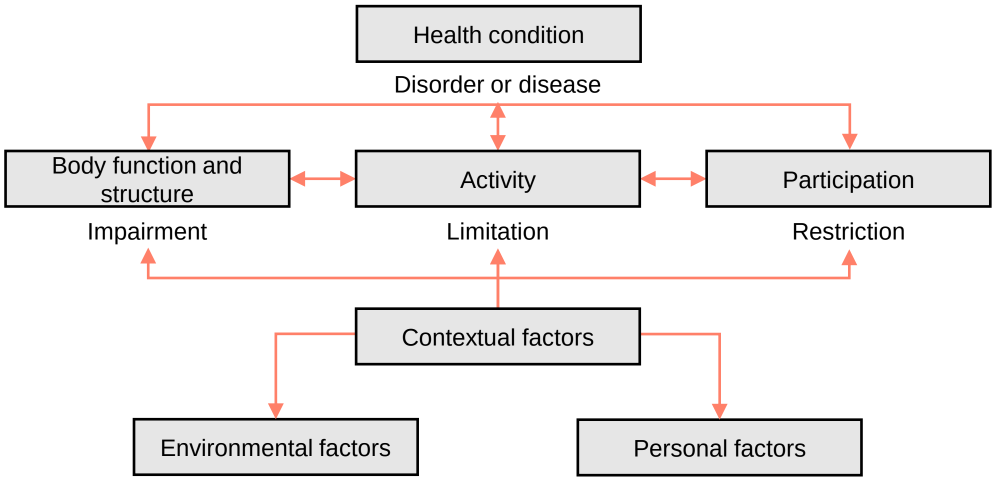


Figure 37: The International Classification of Functioning, Disability and Health (WHO, 2002, p. 9, 2001, p. 18)

The body functions and structure category summarizes physiological aspects and issues considering the anatomy of the body. A lack of function within this category leads to an impairment. Within the activity group, the ability to succeed in work or daily life activities is summarized. A limitation is defined as individual difficulties to execute a task or an activity. Participation describes the possibility to be part of an activity or event. If that's not possible for a person, we talk about a restriction. (WHO, 2001, p. 10)

Contextual factors influencing the human consist of external environmental factors that include the physical and socio-cultural contexts e.g. climate, products, services and technology and internal personal factors including the personal and demographic background (Lenker and Paquet, 2003, p. 5). Thus the ICF model provides a useful framework for assisting technology intervention outcome research. Usually the assessment of assisting technologies is based on the evaluation of user benefits and user acceptance (Lindwedel-Reime *et al.*, 2016, p. 19), referring to the clusters of activity and contextual factors. The limitations of the ICF model result from its lack of temporal and causal components, which are necessary in order to develop a predictive model for outcomes research (Lenker and Paquet, 2003, p. 5). Further, while the ICF can be used to identify assistance needed to improve the functioning of individuals and counteract impairments, limitations and restrictions, a structured selection of suitable assistive devices is not supported by the framework and no implications for the use of assisting systems can be derived from it. (Scherer *et al.*, 2007, p. 3)

Considering an ageing workforce this need for assistance is especially pronounced in the physical domain. Studies analysing the connection between workers age, ability decline, and perceived strain levels, particularly with the investigation of physical limitations of older workers, have been conducted for several years in different industrial occupations. The results reported show that at a constant stress level, the perceived strain increases as a function of workers' age (Aunola *et al.*, 1978, 1979; Ilmarinen and Rutenfranz, 1980; Börner, 2019).

Several authors pointed out the need for redesigning workplaces (by making them adaptable to the employees' ages and characteristics), or for developing adequate initiatives to enhance the productivity of elderly workers, such as retraining, wellbeing improvement and human resource involvement

(Shephard, 2000, Zaeh and Prasch, 2007; Prasch, 2010; Keil and Spanner-Ulmer, 2012; Reinhart and Egbers, 2011; Egbers, 2013, Rademacher *et al.*, 2013 and Bures and Simon, 2015) Therefore, the utilisation of advanced supporting technologies not only can provide improved work conditions but also offers workers the opportunity to prolong their careers (Calzavara *et al.*, 2019; Gonzalez and Morer, 2016). Assistance systems serve to relieve the physical stress on the workforce and are becoming increasingly important for performance-limited workers, as the assistance functions can be different (Schenk *et al.*, 2014, p. 619).

Age and ageing are usually understood as a process that can be managed with the help of technology in assistance system development projects (Weidner and Karafillidis, 2018). Permanent support can also have negative long-term effects on the skeletal muscle system. (EUOSH, 2019b), thus the assistance provided by systems should be a function of age as suggested by Weidner *et al.*, 2015. As illustrated in Figure 38 the need for assistance increases with workers age caused by physical ability decline and limitations.

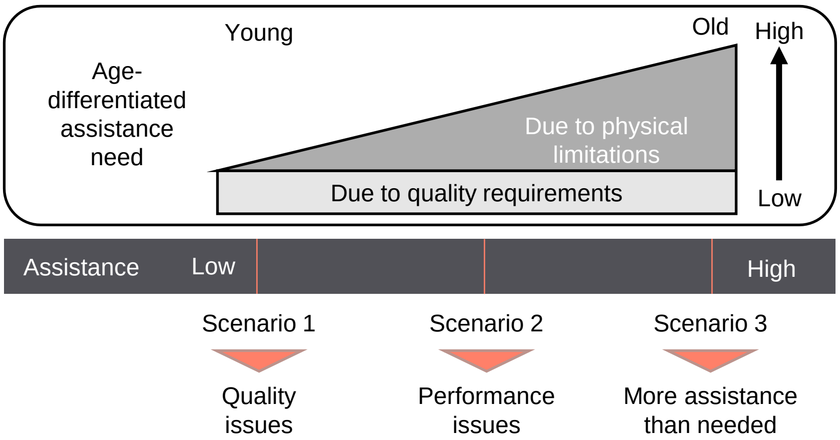


Figure 38: Age-differentiated assistance need [based on (Weidner *et al.*, 2015, p. 18)

This indicates that the assistance provided should be a task related and a function of workers age, so that age- and task-related aspects can be compensated, but not more assistance than needed should be provided, to prevent performance or health issues (Weidner *et al.*, 2015, p. 17)

In the assessed literature only the approach developed by Spillner is based on a systematic evaluation of physical assistance needs. Spillner suggests to record employees' skills or work restrictions and work requirements to determine the need for assistance from the difference between the associated capability and requirement characteristics. A numerical values proportional to the quality of the characteristics is assigned. If requirement values exceed ability values a need for support is quantified. Further, for the comparison of the need for assistance between different characteristics, a standardization according to the ability limit is suggested (Spillner, 2014, pp. 112–115)

$$\text{Need for assistance} = AN_{wpa} = TC_{ap} - AC_{wp}$$

$$\text{Standardized need for assistance} = ASN_{wpa} = \frac{TC_{ap} - AC_{wp}}{AL}$$

$$w \ldots \text{worker}, p \ldots \textit{profile characteristics}, a \ldots \textit{worktask}$$

$$TC \ldots \text{task characteristic}, AC \ldots \text{ ability characteristic}, AL \ldots \text{ Ability limit} = max\ (ACwp)$$

The requirements determined in this way can then be summarized and analysed with regard to selected characteristics, employee groups, and workstations. Useful characteristics are the frequency or magnitude of single assistance needs to identify priorities for action, the maxima of the need for assistance in order to find the respective highest requirements and enable deployment of all employees, or individual comparison of ability and requirement for each work tasks to derive individual solutions. Further, a search for groups and pattern in the distribution of assistance needs, can be beneficial to derive one solution for several work place or groups of workers. Based on the need for assistance robotic solutions can be searched, planned and developed. (Spillner, 2014, pp. 112–115)

The approach suggested by Spillner can be used to derive assistance needs and identify suitable assistance functions, but impose high requirements in terms of complexity, resources (workplace data on tasks level, employee data for a multitude of abilities, etc.) and standardization of work. As mentioned before, besides the highly standardized automotive industry, usually companies do not process data about work task characteristics and worker ability assessments. Thus, other criteria to evaluate the need for assistance to identify suitable solutions and evaluate worker benefits are needed.

2.5.9 Evaluation of assisting technologies

To judge the feasibility and improvement of a process technology solution for work improvement an evaluation after its implementation is necessary and several metrics were suggested in scientific literature. Usually performance metrics for the assessment of physical assistance systems measure health and safety, utility and cost-benefit metrics (Crowell *et al.*, 2018, pp. 23–43).

2.5.9.1 Health and safety metrics

The assessment of health and safety impacts of assisting systems is a complex and ongoing topic of research. Daub, 2017 summarized influencing factors for body-worn systems, concluding that there is more data required in the three areas of (1) diseases and risk factors, (2) the analysis of diseases, (3) pathogenesis of MSD and associated workplace risk factors. Moreover, for the evaluation of assisting systems in terms of their benefits in relation to industrial work tasks (pre-post-tests), effects on health complaints (continuous screening) and long term effects (longitudinal designs) scientific studies have to be conducted. In Figure 39 the complex relationships that are involved in the evaluation of physical assistance systems are shown. For an easier analysis, health and safety metrics can be sub divided in ergonomic, biomechanical and operational improvement considerations (Crowell *et al.*, 2018, pp. 23–43), as detailed in the next sections.

Ergonomic metrics can be used for the assessment of workplaces and related stressors that can lead to health impairments. Usually this metrics are assessed with ergonomic workplace assessment methods (see section 2.4.3). For the evaluation of physical assisting measures in terms of health and safety, different ergonomic metrics including biomechanical, physiological and operational metrics can be used.

Biomechanical performance metrics are physical measures that quantify the movement or structure of a system. For the assessment of physical assisting systems postural stability, kinematic and kinetic metrics are of interest. Postural stability assessments can be used to evaluate how specific conditions (e.g., injury, disability, load), or interventions (e.g., training) influence balance or stabilization. Metrics of interest include ground reaction forces, deviations in centre of pressure (COP), limits of stability, and dynamic postural stability index. Postural stability can be measured using force platforms and pressure sensing systems in laboratory studies and COP has been measured in industrial case studies utilizing pressure-sensing insoles integrated into footwear. (Crowell *et al.*, 2018, pp. 24–25; Grazi *et al.*, 2019 - 2019, p. 402). Kinematic metrics describe the motion of the body without considering forces associated with those motions. Common metrics of interest include joint angles, ranges of motion (ROM), and joint velocities. These metrics can be determined using dynamic motion capture systems (optical, video, and IMU-based) or static inclinometers and goniometers. For industrial application there are no current systems. (Crowell *et al.*, 2018, pp. 27–28) Kinetic metrics are used to assess the forces associated with motion. Typical kinetic metrics include ground reaction forces (GRFs), loading rates, internal joint forces and moments, and powers. Kinetic measurements can also be conducted by means of motion capture systems in conjunction with force measurement and simulation software, but computer models have not yet been developed and validated yet. (Crowell *et al.*, 2018, pp. 29–30)

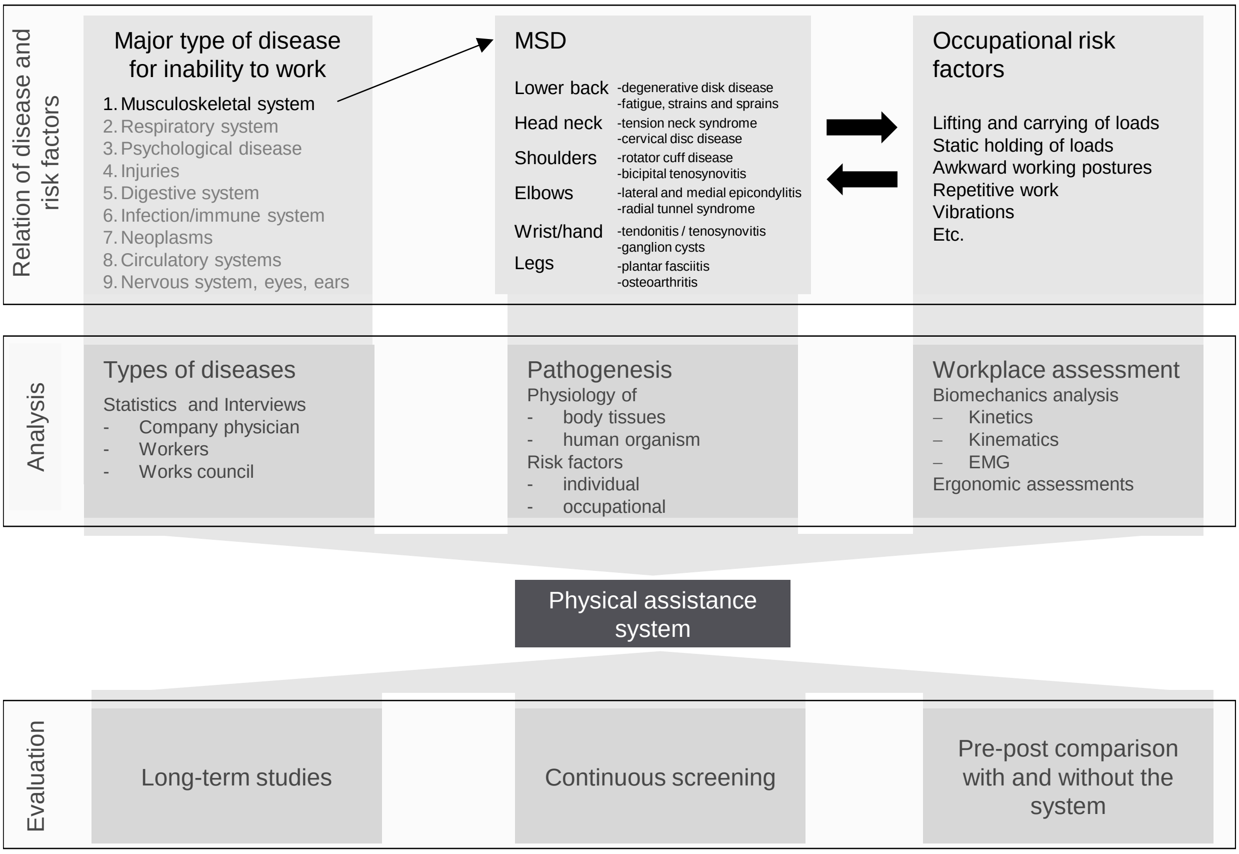


Figure 39 :Assessment of physical assisting systems from a medical point of view (Daub, 2017, p. 496)

Physiological performance metrics, are quantitative measures of the physical and chemical phenomena in a biological system. For the assessment of assisting systems physiological factors to be considered include metabolic, muscle function and strength as well as endurance metrics. Metabolic cost is typically quantified by measuring the rate of volume of oxygen consumed. Metrics to evaluate the energy expenditure include besides the rate of and the maximum oxygen consumption, the energy turnover, heart rate, heart rate variability, respiratory exchange ratio, skin temperature and galvanic skin response.(Crowell *et al.*, 2018, pp. 30–32; Grazi *et al.*, 2019 - 2019, p. 403) Cardiopulmonary testing equipment as the indirect calorimetry or spiroergometry allows the measurement of all relevant metabolic metrics (Knott, 2017a; Knott, 2017b), and heart rate measurements can provide information about the global fatigue level (Grazi *et al.*, 2019 - 2019, p. 403). Muscular strength and endurance can be measured as isometric peak force or torque. Besides peak torques also the torque development, the average work, and the vertical jump high can be considered as metrics to assess strength and endurance. Current measurement technology allows the measuring of all relevant parameters with dynamometers or mechanical and optical systems. (Crowell *et al.*, 2018, pp. 33–34) Further, the relative level of muscle contraction can be measured via electromyography (EMG) measures including peak EMG, integrated muscle activity measurement (Crowell *et al.*, 2018, pp. 32–33). In addition, EMG peak value, root mean square and integral of the EMG linear envelope can be used to measure the level of muscle activation. Muscular activity can also be reported as percentage of the maximum voluntary contraction (%MVC) to allow inter-subject comparison. Further, mean and median frequency of the EMG spectrum can be used to determine the level of muscular fatigue in prolonged tasks. (Grazi *et al.*, 2019 - 2019, p. 403)

Operational strength metrics can be used to assess if a person has the strength to fulfil a task. Typical test include box lifting or stacking where performance metrics include overall time to complete a certain number of lifts, or the number of repetitions in a given time. **Operational movement metrics** can be used to quantify performance on a variety of tasks that simulate the types of movements that might be carried out during work. Movement metrics are measures of time to complete a task or distance travel. Test may include typical activities as sitting, kneeling squatting or crawling. These metrics can be assessed by FCE (see section 2.2.7) or similar tests. (Crowell *et al.*, 2018, pp. 35–40)

2.5.9.2 Utility metrics

Worker perception, technology acceptance and system usability are important factors determining the subjective wellbeing and thereby the continuous use of assistance systems**.**

Human factors metrics are used to understand the interactions between user and system including its environment in order to optimize functionality, human comfort, safety, and overall system performance. Human factors metrics include fitting and sizing metrics, usability and equipment compatibility metrics and training metrics. Fitting and sizing metrics are used to assess a system in terms of the attachment to and position on the user’s body as well as the range of body dimensions. Common metrics include anthropometric fitting (size and body dimensions), the ability of the user to put on or remove the system and self-adjustment capability. (Crowell *et al.*, 2018, pp. 41–42)

User acceptance and usability metrics are used to determine the utilization of a technology. User acceptance describes if the intended users are willing to employ a system and sser acceptance metrics are used to determine if a user would use the systems provided (Davis, 1989). Usability describes the extent to which a system, product or service can be used by specific users in a specific context to achieve specific objectives effectively, efficiently and in a satisfying way (ÖNORM EN ISO 9241-11, 2018, 9, 14). Usability metrics are used to determine whether a system is field capable and if it provides the functions needed. These metrics are dependent on the operational context in which a system is expected to perform and include performance, user acceptance, and usability issues. Common acceptance and usability metrics include perceived usefulness, the ease of use, efficiency, effectiveness, satisfaction, and systems reliability(Crowell *et al.*, 2018, p. 42; ÖNORM EN ISO 9241-11, 2018, p. 39). To assess acceptance and system usability different questionnaires and scales were developed as for example the System Usability Scale (SUS) by Brooke, 2014, or the Technology Acceptance Model TAM by Venkatesh and Davis, 2000.

Equipment comparability metrics can be used to determine the degree to which a system integrates with other, standard equipment systems and with the system as a whole. Equipment compatibility metrics may include weight and weight distribution, mobility, compatibility. (Crowell *et al.*, 2018, pp. 43–44)

Training metrics describe the degree and type of instruction required for successful operation of a system. Typically, metrics include the instruction time, habituation time, familiarization, ease of understanding, and physical fitness requirements. Most of the human factors metrics can be accessed via observations, questionnaires, and interviews. (Crowell *et al.*, 2018, pp. 42–46)

2.5.9.3 Cost metrics

Cost metrics can be used to judge the benefits of an intervention from an economically point of view. Cost metric can be expressed by the KPI of return on prevention (ROP). The ROP compares direct and indirect costs of illness related absences, investment and operating costs for an intervention measure to the savings due to improved working conditions. (Spillner, 2014, p. 78; Bräunig and Kohstall, 2013, pp. 17–18) Thus, the ROP describes the relationship between the monetary prevention benefits and the prevention costs. While costs of occupational prevention are directly measurable, benefits can only be evaluated indirectly (Bräunig and Kohstall, 2013, pp. 17–18).

Direct and indirect cost of sick leaves are directly assessable by costs due to incapacity to work, production downtime and loss of gross value added. Further, cost of chronic illnesses can be used as a metric (see Section 1.1.2). Cost for measure implementation include investment costs and operation costs for the system, which can be estimated with a low level of uncertainty. Information to be considered for cost estimation include procurement and implementation costs, both related to the technology readiness level, and operating costs which are related to resource needed by the systems (Spillner, 2014, p. 78).

However, the evaluation of related savings is a complex topic. Benefits can, on the one hand, result for quality, time and cost issues and, on the other hand, in reduction of strain and related health impairments. Considering this domain, cognitive assisting devices can, for example, support workers in remembering information, procedures and correct tool setting during production to avoid failures, as well as help in faster learning and training, thus improving productivity and quality and minimising idle times (Takahashi *et al.*, 2016; Yuan *et al.*, 2008; Ong *et al.*, 2008). Further, improved setup-, execution- and process times, as well as increased precision can result from physical assisting systems (Dahmen and Constantinescu, 2018, p. 679; Dahmen *et al.*, 2018a, p. 1279). Nevertheless, cost metrics can only partially be assessed directly and usually have to be estimated prior to implementation as for example for long-term health benefits and saving can only be estimated (Bräunig and Kohstall, 2013, p. 18). Thus, evaluating the monetary benefit of applying such technologies is a complicated topic.

In terms of health outcomes, evaluating the prevention benefits of applying physical assisting technology is a highly complex and broad field of application depending on the technology used, the fit between worker, workplace and technology, possible positive and negative health and safety outcomes, the perceived utility of the system, and economic issues. Therefore, a general valid way to assess assisting systems is not available yet. For stress reducing stationary process technology ergonomic improvements can be assessed by re-evaluating the workplace with standard tools after implementation. However, for most strain reducing body-worn tools ergonomic assessment procedures to evaluate the impacts on the operator are missing (see Hefferle *et al.*, 2020; Hensel and Steinhilber, 2018; Spada *et al.*, 2018, p. 243; Grazi *et al.*, 2019 - 2019, p. 400; Dahmen and Hefferle, 2018, p. 17). This is due to a missing connection of study results and a comprehensive ergonomic assessment method for wearable systems, as existing studies focus on specific body parts, but do not present results in a simplified ergonomic score that indicates the impact on the workplace risk (Dahmen and Hefferle, 2018, p. 19). Moreover, a challenge in ergonomic assessment derives due to the fact that these systems do not directly change the stress determining factors. As only the experienced strain is changed by wearing such systems, evaluation of effects on workplace risk is even more complicated (Dahmen and Hefferle, 2018, p. 8). Only few suggestions on how to conduct such an assessment are available in literature, mainly adapting scoring values based on experience and estimation (Dahmen and Hefferle, 2018, pp. 23–24). Therefore, there is a strong need for action to derive suitable assessment procedures to overcome current individual time-consuming, impractical, and highly cost intensive practice (Theurel *et al.*, 2018). Without a valid assessment approach, considering advantages and disadvantages of wearable physical assistance systems and linking it to the need for assistance, there is no objective decision support whether a device should be integrated into a production system or not.

However, to capture the benefits of technology in solving problems of an ageing workforce, enterprises will need to invest a large amount of money in new ergonomic equipment that is designed to meet personal needs. Moreover, some systems are in an early stage of development, expensive, unreliable and oversized (Davies, 2015, p. 5). As mentioned before, exoskeletons offer significant potential to provide individual, flexible and task-specific physical assistance for declining abilities to support employees with physical disabilities in the context of inclusion or reintegration into the workplace (Hensel and Steinhilber, 2018, p. 107), but information on worker's acceptance and long-term use and health effects are needed. Industry experience can reveal obstacles to worker's acceptance that are not evident in a controlled laboratory environment, therefore more studies situated in real application context are needed (Spada *et al.*, 2018, p. 244).

2.5.10 Summary of assisting technologies

As a consequence of the rapid evolution of work across industries, the factories of the future will have high cognitive demands, but also physical strenuous work. This leads to a dramatically increased need for assistance in relation to the group of older workers. Technological assistance can be of cognitive, collaborative or physical nature. Several dimensions of assisting systems can be distinguished and the provided assistance can impact workers on different levels e.g. employee health or operational KPI improvement. In relation to this thesis the impact on workers' health is considered as the central factor for further considerations. To achieve this, a fit between the task, the worker, and the technology is necessary, as explained in the task-technology-fit concept. To achieve such a fit, the selection of suitable technologies is a complicated cost intensive process, involving several work, human and technology related factors. These factors can be evaluated based on several different metrics, as shown in this section. Currently available literature for physical assistance technologies revealed that exoskeletons in particular show high potential in relation to the topic at hand and this technology group is investigated more in detail in the next section.

2.5.11 Exoskeleton technology

Exoskeletons were originally developed for medical rehabilitation and the military sector but are becoming of increasing relevance for industrial work places (Hensel and Steinhilber, 2018, p. 107). Based on their origin, the devices are aimed to support physically weak, injured, or disabled people to perform motions involved in activities of daily living (DeLooze *et al.*, 2016, p. 671). Exoskeletons could be useful to lower workers' fatigue, thus leading to increased alertness, productivity and work quality, to reduce work related musculoskeletal disorders and the physical support to keep experienced personnel in the work force (Spada *et al.*, 2018, pp. 237–238). Positive effects on work stress reduction have been reported, especially for passive exoskeletons that are further developed as their active counterparts. In industrial applications especially wearable exoskeletons to assist operators during manual handling tasks and awkward positions will play a major role (Spada *et al.*, 2017; Theurel *et al.*, 2018; Calzavara *et al.*, 2019).

2.5.11.1 Task-technology-fit for exoskeletons

As shown in Table 9, for the challenges imposed by the characteristics of high work tasks and work stresses such as variance, small batch production of individual products with high flexibility requirements and users with individual different need for physical support in terms of force, mobility, or endurance, the most promising solution seems to be in the technology of exoskeletons. Especially, when technical and organizational design measures have been exhausted, or when other preventive measures are not feasible, or effective a targeted use of exoskeletons in production and logistics could reduce physical stain for employees and help to improve working conditions (Hensel and Steinhilber, 2018, p. 107; Spada *et al.*, 2018, p. 237) and as a preventative measure for musculoskeletal disorders (Hefferle *et al.*, 2020, p. 50). Thus, this can be very beneficial for the elderly group of workers.

A simple approach of matching assistance systems with workplaces for assembly tasks in automotive industry, with a focus on exoskeletons, was suggested by (Voilque *et al.*, 2019). This approach is based on classifying ergonomic risks derived from workplace assessment and three use cases for awkward posture assistance, heavy workload manipulation and assembly efforts. The use case awkward posture /

movement support covers processes where the operator is required to maintain or repeat an awkward posture or movement. Here the technology has to support the worker's body mass and the mass of a tool used. This use-case concerns work performed in constrained body postures as for example in-car assembly, trunk bent forward, keep arms raised above the shoulders and standing for a prolonged duration. The use case heavy workload considers manipulation handling of masses over 4 kg. Here, assistance should be provided to compensate the load of the handled object when the compensation by dedicated tools or manipulators is limited due to the wide variety of different shapes and masses. Use case three summarizes assembly efforts applied in various directions. The workstations concerned are mostly on manual assembly lines, and assistance is needs for the upper limbs in high dexterity tasks carried out under space and force constraints, sometimes in repetitive effort. (Voilque *et al.*, 2019, pp. 14–15) This use case classification only takes into account workplace characteristics and ignores user requirements and the qualification or quantification of an assistance need, but is useful to allocate technologies according to work places.

A promising solution to match exoskeletons and workplaces based on a portfolio matrix was suggested by Goehlich *et al.*, 2016. The procedure includes four steps: creation of a classification list with quantitative and qualitative ergonomic system features, creation of a worker demand survey to identify expectations and requirements, clustering of support characteristics of the technology, and visualization of the result matrix (Goehlich *et al.*, 2016, p. 150). As characteristics for support systems in aeronautics industry the clusters of robustness (physical support and safety), acceptance (wearing and response time and user experience) and agility (impairment of body movements) were defined. The results can be displayed in a 2D or 3D portfolio matrix and compared to system characteristics to identify suitable solutions (Goehlich *et al.*, 2016, p. 153). An example of a 2D portfolio is presented in Figure 40. Ergonomic requirements from the aeronautic industry a group to clusters and the worker demand is shown. Further, the support of an exemplary system is added to illustrate the fitting of system and requirements.

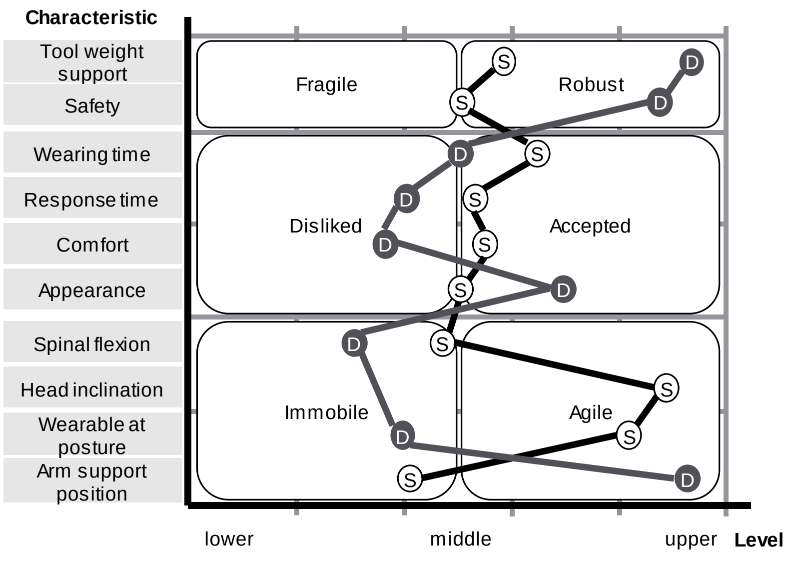


Figure 40: Portfolio matrix with demand (D) and support (S) profiles [based on (Goehlich *et al.*, 2016, p. 153)]

The approach offers a simple decision support and the use of well-known portfolio illustrations is beneficial to communicate the information to decision makers. A further advantage of this approach is the inclusion of the worker demand and expectations via a survey tool, which allow to assess the individual demand for support. However, this approach is tailored for ergonomic stress in the aerospace industry which is quite different from other industrial environments and provides individual and specific work conditions (cf. Goehlich *et al.*, 2016, p. 149). Further, physical support is considered only in terms of tool weight support and the limitation of body movements, ignoring most types of support needed in manufacturing and logistics work.

A more detailed method in relation to exoskeleton technology to relate technologies and workplaces was suggested by Linnera *et al.*, 2018 for construction work. In this approach, work was categorized in three levels, the housing construction (Level 1) which can be subdivided into basic task categories (Level 2) and then further into individual task areas (Level 3) and compared to functions offered by exoskeletons. The exoskeletons were classified according to the body part supported (task range) and their actuation (magnitude of possible support). Technology appropriateness was evaluated through a pairwise analysis of task areas and types of exoskeletons, clustering the appropriateness of different technologies in high, medium, low and not applicable. Four general usage scenarios for exoskeletons in this industry were identified based on patterns. These scenarios include: Work tasks with preferred lower limb exoskeleton usage (1), applicable for all tasks assessed including foundation works, on-site operations, structure construction, building service, interior and exterior finishing, landscaping, site measuring and monitoring and civil works. Work with preferred body extension assistance (2), which are mostly tasks dealing with heavy physical work as foundation work (excavation, canalisation work, etc.), on-site operations (logistics, lifting, machinery installation, etc.) and structure construction (concreting, steel installation and welding, etc.). Work tasks were body extension is not applicable (3), including building services (all types of electronic installations) and internal and external finishing (grinding, plastering, painting, masonry, insulation work, roofing and sealing work, plumber work, etc.). The last hotspot identified deals with fully body support (4), including landscaping work tasks (metal works, lighting, greenings, etc.), site measuring and monitoring (investigations, surveying and monitoring work) and civil work (street works, underground work, etc.). Further, three task clusters were identified for which no exoskeleton support system could be found at present markets. (Linnera *et al.*, 2018)

The construction specific sub-classification can be useful to merge technology of exoskeletons to tasks clusters in the building industry. Furthermore, the approach using a pairwise comparison offers the possibility to find suitable assistance solutions for work related stressors. Disadvantages of this approach are, that the analysis on tasks clusters level do not offer enough information to match assisting functions and work tasks. Apart from that further conclusions are also only possible to a limited extend, as the construction industry differ strongly from industrial manufacturing and logistics work in types of work tasks and work stress.

Finally, Dahmen *et al.* presented an approach to match exoskeletons and works stress with a method called “exomatch”. In this method exoskeletons are searched according to work tasks, based on different individual factors and matching rules. Output of this method is a ranked list of the top fife matching exoskeletons, each of whom is presented stating the advantages and disadvantages. Core of the approach is a translation of workplace conditions into exoskeleton requirements for production environmental (material, hygiene, power supply, etc.) and ergonomic (load, weight, time, etc.) factors. A decision for a suitable exoskeleton should be made based on threshold values that can be adapted to external influences. The match of workplaces and exoskeletons is conducted with matching rules, which are implemented as matching tables. These tables are based on a weighted score system that enables a summarized score-value of the supporting capability. As planning objectives best usability, best ergonomics, best price, and ad-hoc established criteria were suggested and weighting factors like maturity and costs were implemented. (Dahmen *et al.*, 2018b)

Further, an integration method for exoskeleton application in repetitive tasks and strongly plannable processes (standardized line assembly) based on the exomatch method was suggested by Dahmen *et al.* (Dahmen *et al.*, 2018a). The methods suggested are suitable for conducting a preselection of exoskeletons, based on special requirements and conditions from planner and workplace perspective.

Therefore, reasonable exoskeleton-workplace combinations can be identified. However, the method is extensively time consuming and restricted in terms of flexibility and adaptability. For an application in workplaces with several tasks and changing conditions the method is not suitable (Dahmen *et al.*, 2018a, p. 1278).

2.5.11.2 Evaluation of exoskeleton technology in industry

A standardized ergonomic intervention method for the assessment of technological measures has to include objective and subjective outcomes (Hefferle *et al.*, 2020, p. 55). This implies that the evaluation has to be conducted in a two phase approach, as the objective measurement of physical data is mainly applicable in lab-testing and the subjective evaluation is only meaningful in the real application context. Further, if the general functioning of a solution has already been proven for specific tasks in lab-testing, the results can be transferred and only the subjective evaluation in the application context is necessary.

In testing of exoskeletons two different scenarios have to be distinguished. If the general function and applicability of the solution for the chosen tasks is under consideration, laboratory testing of the measurement is necessary. Lab-testing offers the possibility to conduct a quantitative experiment with controlled conditions. On the other hand, if the general function of the technology for the intended application is proven, further testing of the specific assistance and limiting factors for the actual work situation are necessary (Hefferle *et al.*, 2020; Börner, 2019, p. 54). However, in both settings the testing procedure usually consist of a comparison of the stress and/or strain experienced during the execution of specific work tasks with and without the assisting system, as in so called pre-post (quasi) experimental research designs (Döring and Bortz, 2016, p. 209). For lab-, or pilot-testing the application of a quantitative experimental design is suitable, which offers benefits in terms of the internal validity as the setting and the confounding variables can be controlled (Döring and Bortz, 2016, pp. 94–95). In such a design the application of measuring technology is possible (Döring and Bortz, 2016, p. 323). Disadvantages of such testing is that the complexity of reality cannot be taken into account in isolated laboratory investigations and the transfer of results to the real application context is limited (Döring and Bortz, 2016, p. 206). In addition, such test designs are not suitable for in-line testing in industrial settings as they influence the execution of work heavily and do usually not allow a conclusion for the subjective experiment (Döring and Bortz, 2016, p. 503).

In the real application context however, a qualitative approach based on a field study setting is suitable (Döring and Bortz, 2016, p. 206). Such a setting offers benefits in transferability of the results to practice and requires a high external validity. The external validity refers to the generalizability of the results, i.e. transferability to other places, times, effect variables, treatment conditions or persons. (Döring and Bortz, 2016, p. 95) Thus, the results of a field study can be used to derive practice-relevant recommendations that can be transferred to reality (Döring and Bortz, 2016, p. 106). Therefore, in the real application context, field studies are advantageous as the setting is not controlled. Disadvantages of field study designs include the limited accuracy of control, as the conditions in the field cannot be specified. Therefore, also confounding variables have to be taken into account by recording them during data collection and including them as control variables in the evaluation. (Döring and Bortz, 2016, pp. 199–201). In this context a quasi-experimental approach, that combines the benefits in relation to external (Döring and Bortz, 2016, p. 206), is a suitable approach to conduct a practise relevant and scientifically grounded testing.

The methods to be used in evaluation also differ according to the aim chosen. If the aim of the project is a reduction of work stress, **objective physical measurements** of the work stress have to be conducted. This can either be done by re-assessing the assisted work tasks with ergonomic assessment tools on a detailed level, or by measuring physical reactions at the workplace before and after implementing the intervention measure. Measurements that are useful to analyse the human reaction on stress were summarized by Börner, 2019. Objective parameter measurements include the conduction of an electrocardiography (ECG), electromyography (EMG), electrooculography (EOG), electroencephalogram (EEG), measurement of the body core temperature and determination of the flicker fusion frequency (Börner, 2019, p. 20). If the aim of the project is an age-appropriate adaption of the work strain, questionnaires collecting self-report data are a suitable tool, that can be used with a low amount of resource input needed (Döring and Bortz, 2016, p. 504). Methods for **subjective self-assessment** of work strain include perceived work strain grading (Borg, 1978), the (subjective) evaluation of strain reduction in different body parts (Corlett and Bishop, 1976). Further, the determination of the effects on the subjective work ability (Tuomi *et al.*, 1997), and the evaluation of perceived improvements caused by the measure (Kaltenbrunner and Spillner, 2013; Baltrusch *et al.*, 2018) can be assessed using standardized questionnaires. Especially, standardized and validated questionnaires are suitable, as they enable the subjective evaluation of the experienced situation (Döring and Bortz, 2016, p. 398). In addition, questionnaire surveys are more discreet and anonymous from the interviewees' point of view so that, sensitive and intimate topics as work strain in relation to physical capacity can be better investigated (Döring and Bortz, 2016, p. 398).

Standardized assessment of general **objective** effects of body worn interventions include metabolic measurements (Groos *et al.*, 2020; Hefferle *et al.*, 2020), and measurement of physiological data (Glinski *et al.*, 2019; Lotz *et al.*, 2009; Whitfield *et al.*, 2014; Theurel *et al.*, 2018; Groos *et al.*, 2020) for overall (whole body) evaluation. For body part evaluation, muscular activity measured with EMG or NIRS (Lanotte *et al.*, 2018; Abdoli-Emeraki and Stevenson, 2008; Whitfield *et al.*, 2014; Amandels *et al.*, 2019; Picchiotti *et al.*, 2019; Theurel *et al.*, 2018; Hensel and Steinhilber, 2018; Luger *et al.*, 2019b; Weston *et al.*, 2018) and biomechanical measurements of loading (Abdoli-Emeraki and Stevenson, 2008; Whitfield *et al.*, 2014; Amandels *et al.*, 2019; Picchiotti *et al.*, 2019; Theurel *et al.*, 2018; Luger *et al.*, 2019a; Weston *et al.*, 2018) is usually conducted. Further, technical measurements at the used device (Huysamen *et al.*, 2018; Picchiotti *et al.*, 2019; Theurel *et al.*, 2018; Hensel and Steinhilber, 2018; Luger *et al.*, 2019a) are frequently conducted. All studies assessed task related performance indices as tasks conducted, weights manipulated, time needed etc.

Standard assessment criteria for the evaluation of the **subjective** impact of body worn stress and strain influencing solutions generally include the assessment of local discomfort with visual analog scales (VAS) (Baltrusch *et al.*, 2018; Miura *et al.*, 2018), or discomfort Likert scales (Hensel and Steinhilber, 2018; Luger *et al.*, 2019a). Also body maps (Amandels *et al.*, 2019; Hensel *et al.*, 2018), BORG CR10 and rating of perceived exertion (RPE) scales are used for the assessment of pain and strain (Huysamen *et al.*, 2018; Lotz *et al.*, 2009; Alemi *et al.*, 2019; Theurel *et al.*, 2018; Spada *et al.*, 2018, 2017; Alabdulkarim and Nussbaum, 2019).The evaluation of user acceptance can be conducted with different usability scales as SUS, TAM, or UMTX or specifically created questionnaires (Kaltenbrunner and Spillner, 2013; Spada *et al.*, 2018; Hensel *et al.*, 2018; Amandels *et al.*, 2019; Huysamen *et al.*, 2018; Hensel and Steinhilber, 2018; Alabdulkarim and Nussbaum, 2019)

2.5.11.3 Benefits of exoskeletons in industrial work

Exoskeletons can provide different benefits for the company and the worker. In relation to different metrics of health and safety, exoskeletons can reduce stress (active systems) and strain (passive systems). In relation to the utility metrics, exoskeleton as body worn technology are easy to combine with the work environment and worker characteristics and other protective equipment. In relation to cost metrics, exoskeletons can be judged as an affordable solution in relation to stationary process technology, providing a high flexibility and a wide range of applicability and use.

Benefits in relation to stress and strain reduction

Passive systems use materials, springs, or dampers with the ability to store energy, generated by human motion, to support the operator when required in postural work or by body motions (DeLooze *et al.*, 2016, p. 172). Generally, passive exoskeletons were reported to decrease stress in the low-back muscles during lifting, bending and static holding tasks (Baltrusch *et al.*, 2018, p. 94). The application of these exoskeletons can decrease the compression forces at the lower spine by 15% to 29% (Abdoli-Eramaki *et al.*, 2007; Koopman *et al.*, 2019) and the activity of the back muscles by 10% to 48% in dynamic lifting (Bosch *et al.*, 2016; Ulrey and Fathallah, 2013; Whitfield *et al.*, 2014; Motmans *et al.*, 2019), and by up to 44% in static bending tasks (Motmans *et al.*, 2019). Further, during static holding the endurance was reported to increase up to three-fold (Bosch *et al.*, 2016). However, also an increase in the activity of antagonist muscle groups (Ulrey and Fathallah, 2013; Theurel *et al.*, 2018), discomfort at contact areas of technology and human (Motmans *et al.*, 2019) and changes in postural strategies and tasks execution have been reported, as potentially unwanted side effects (Theurel and Desbrosses, 2019, p. 15).

For lower extremity exoskeletons an 11-49% reduction for specific muscle groups with a passive exoskeleton that supports lifting and carrying of heavy loads have been reported (Kim *et al.*, 2013). Thus, the lower extremities are relieved by about 64% in a high sitting posture on the exoskeleton (Luger *et al.*, 2019b, p. 159). Further, reductions of about 67% to 80% of ground reaction forces were found in patient lifting (Hasegawa and Muramatsu, 2013).

Also in subjective evaluation of work exoskeletons support to improve working execution. The rate of perceived exertion (RPE) as a measure for work strain, was reported to be about 16% lower during an assembly task when using an exoskeleton and in prolonged lifting/lowering activities decreased RPE values of 20-25% have been reported (Kobayashi and Nozaki, 2007; Theurel *et al.*, 2018, p. 215). However, with passive exoskeletons usually metabolic costs, or oxygen consumption are not changed on large scale, even if the additional mass of exoskeletons is included (Whitfield *et al.*, 2014). This is also largely applicable for the heart rate that may in some cases even be increased, as shown by several studies (Theurel *et al.*, 2018; Lotz *et al.*, 2009; Godwin *et al.*, 2009). Therefore, Whitfield *et al.* suggested that the introduction of such devices should not be in line with an increase in the work content (Whitfield *et al.*, 2014).

Active exoskeletons are powered by actuators and positive effect on work stress were found for dynamic lifting and static holding. Muscle activity reductions were reported by 30-75% for the shoulder muscles (Muramatsu and Kobayashi, 2014) and by 30-60% for back muscles in dynamic lifting (DeLooze *et al.*, 2016, p. 675), while in static holding a decrease in muscular activity of 30% to 70% for the upper arms and shoulders has been found (Kobayashi and Nozaki, 2007). For active lower limb systems EMG reductions of 20% to 36% in walking, climbing and descending as well as reduced EMG and muscular effort (up to 32%) for sit stand transition or squatting (Yan *et al.*, 2015, pp. 132–133). However, active exoskeletons are not available at the European markets, extensively expensive, mostly very heavy and bulky and suffer from user acceptance problems (Voilque *et al.*, 2019, pp. 15–16; Fox *et al.*, 2019, p. 795). Further, long term health and safe effects are a main market barrier (Motmans *et al.*, 2019, p. 339)

Nevertheless, the positive effects of exoskeletons for different tasks in industrial work outweigh this side effects. In a literature review by Holz this benefits were summarized considering 32 studies related to physical health outcomes in relation to different work tasks. Activities that were analyzed in this report included walking while carrying a load, static holding in stooped and bent position and overhead-height work, as well as lifting and lowering of weights (Holz, 2018, p. 30). Further, with a focus on powered lower limb orthesis and exoskeletons, Yan *et al.* summarized 24 active exoskeletons considering assistance for healthy, elderly and impaired persons (Yan *et al.*, 2015). Also DeLooze *et al.* reviewed 40 papers in which a total number of 26 exoskeletons (active and passive) with an industrial purpose were described. The exoskeletons were most frequently aimed to support stooped working postures, static holding of a load, dynamic lifting of a weight. Some studies also mentioned carrying as an activity to be supported (DeLooze *et al.*, 2016). The subsequent section is a summary of these literature reviews and new research considering exoskeletons.

Benefits in relation to physical work tasks

For **load carrying** contradictory results were found in relation to metabolic costs. Nevertheless, a significant decreases has been reported for range of motion of joints (10-18%) and in muscle activity of the leg muscles (up to 50%) while walking and climbing stairs (up to 53%) (Holz, 2018, p. 57). For **static holding** reductions of muscular activity in relation to upper arm (70%), shoulder (44% to 80%), back muscles (10% to 47%) and leg muscles (20% to 24%) were reported. Further, spinal compression (12% to 18%) and lumbar moments (22% to 43%) were significantly reduced. Moreover, contradictory results concerning RPE values could be observed in the different studies. (Holz, 2018, p. 55). For work at head or overhead level most studies reported declining muscle activity for upper arm and shoulder by 13% to 77% and for abdominal muscles by 50%. Further, an increase in back muscles activity by 31% to 88% depending on the tasks characteristics has been found. Concerning the joint kinematics, a reduction in range of motion in the shoulder by 3% to 10% has been reported. (Holz, 2018, pp. 42–43) For **lifting and lowering** tasks most studies reported a reduction in muscle activity regarding the arms (5% to 46%), shoulders (31% to 80%), and back muscles (10% to 54%). With regard to the joint kinetics a reduction of spinal compression forces (36% to 60%) and flexion-extension moments (17% to 19%) were reported. In terms of effect on the heart rate, contradictory results were found. (Holz, 2018, pp. 51–52; DeLooze *et al.*, 2016, pp. 677–679). For perceived tasks difficulty Baltrusch *et al.*, 2018 examined a static system in a FCE assessment and showed that, while the perceived exertion in three of four tasks potentially assisted by the system declined, it increased in the 9 other tasks (Baltrusch *et al.*, 2018, p. 98). Hensel and Keil showed that the task specific health complaints in assisted body regions can be lowered for static and dynamic work tasks by the use of passive exoskeletons (Hensel and Keil, 2018, pp. 256–257).

2.5.12 Summary exoskeleton technology

Overall, the conclusion can be drawn that exoskeletons are beneficial in reducing the activity of specific muscles for specific work tasks. Further, they can be very beneficial for reduce the load in the lower back and spine. Further conclusions should not be drawn from this research as the type of exoskeletons (active, passive) and the type of work tasks tested in the studies differ widely. Although there a several studies assessing the effects of exoskeletons in laboratory settings, meaningful application studies in real context are lacking (Theurel *et al.* 2019). Moreover, missing understanding of the biomechanical effects in exoskeleton-assisted work tasks and missing ergonomic evaluation tools that specifically address the risk factors influenced by the use of passive exoskeletons are barriers for implementation (Spada *et al.*, 2018, p. 244). Even though there are about 31 commercial industrial exoskeletons OEMs (Marinov, 2020), and several evaluated passive systems at the market, the usage of such devices remains minimal due to the gap between user requirements and system specification, a lack of standardization and bench-marking for industrial exoskeletons and missing selection and decision support (Jawad *et al.*, 2019). However, as outlined in this chapter this technology offers high potential in relation to strain control as beneficial for elderly workers in physical work.

3 RESEARCH NEED AND DERIVED QUESTIONS

In this chapter the conducted literature study is concluded and a comprehensive understanding of the existing knowledge is developed. The three topics of ageing, workplace design and technological possibilities to assistance are connected and identified knowledge gaps are summarized: Further, the scope of work is delimited. Based on that, the objective of this thesis is further refined and the research leading question is broken down into concrete research questions.

3.1 SUMMARIZING THE DISCUSSED LITERATURE

Considering **worker abilities** and their changes while ageing literature analysis clearly indicates that the topic of elderly workers is more than ever of importance for industrialized countries, as birth rates stay low and average population age steadily increases. Findings suggest that the amount and severity of health limitations increase with age. Musculoskeletal disorders deriving from physical miss-loading are the most frequent problem, followed by psychological disorders. These two groups of occupational diseases account for about 40% of all sick leave days recorded steadily over the past years. In terms of WRMSD especially the lower back is an area at risk. Overall there is a strong biomechanical evidence that the exposure to physical loading in the workplace, especially considering heavy physical work, lifting or pushing and pulling of heavy goods as well as prolonged standing promote the development of MSDs, especially in relation to the cumulative dose of exertion. Therefore, especially physical work stress concerning the lower back area is relevant considering ageing industrial work systems.

Ageing is related to a general change of most abilities and skills. While physical and sensory abilities decline, cognitive skills show no general tendency of change and increasing work experience, knowledge and social skills are seen as advantages of employing older workers. Especially, the physical performance factors of muscular strength, endurance, and range of motion are essentially necessary for maintain performance and work ability, but are also significantly declining with age, but (Kenny *et al.*, 2016, p. 8). Although there is a consensus in scientific literature that physical skills generally derogate, there are little detailed qualitative statements about the dependency of performance and age in industrial employment (Scheller et al. 2015, p. 139). Therefore, consequences for the occupational practice cannot be deduced (Wittemann, 2017, p. 21). Few studies showed significant correlation for declining skills and age and a resulting increased perceived strain level at the same work stress for specific abilities or tasks (Scheller *et al.*, 2015; Wittemann, 2017; Rademacher *et al.*, 2013), but no general conclusions can be derived. This is due to the fact that the assessment of individual abilities is too complex, time consuming and expensive for industrial companies (Müglich *et al.*, 2015a, p. 2). Therefore, the few available studies refer to data in industrial companies, only available in a few German automotive companies. From the literature analysis, it has become evident that there is a significant relation of age and increasing perceived strain for constant workloads as a result of ability decline for manual material handling and different body postures and movements (Börner, 2019; Aoyagi and Shephard, 1992). Therefore, workplace redesign for elderly worker populations is necessary in predominately physical work (Ilmarinen, 2001; Prasch, 2010; Spillner, 2014; Walch, 2011). General recommendations on workplace redesign and age based limit values are available in literature but these are not specific enough to derive solutions in industrial practise.

In terms of work and working conditions findings from existent literature show that ddespite the on-going trend in automation and mechanization in industry, many workers are still exposed to physical workload due to material handling (32% in the EU), repetitive movements (60%) and awkward body postures (43%) (Eurofound and International Labour Organization, 2019, p. 17). Despite the technological advances made under the umbrella term Industry 4.0 automation and robotics are still far from being able to perform work in dynamic and flexible work environment and in variant rich small batch production. Therefor the worker will keep playing a central role in manufacturing and warehousing environments, with a high product mix and relatively small order sizes (DeLooze *et al.*, 2016, p. 671) (Deuse *et al.*pp. 99). Even though, new technological developments have offered new ways to reduce physical work demands, some workstations are and will remain physically stressful and will involve awkward postures (Voilque *et al.*, 2019), especially in manufacturing and logistics work.

Considering **work place assessment literature**, the conclusion can be drawn that awareness and systematization are important issues for the evaluation of physical work load and the derivation of ergonomic measures (Deml *et al.*, 2016, p. 434), but this awareness and systematization is often missing in operational practice. Therefore, economic, and easily applicable and understandable assessment procedures (screening procedures) are necessary for industrial use. Considering ergonomic workplace assessment, the literature study showed that there are several different approaches available. These approaches are designed for specific purposes and of limited transferability. For example, in evaluating action forces, national German and classical limit value approaches are of limited applicability in most workplaces in industries where work is not performed in an upright position (e.g. retail, automotive, heavy machinery assembly, aircraft and marine industries) as the force data was collected in such a position (Schaub *et al.*, 2015b). Figure 41 summarizes the different sources of ergonomic risks at the workplace, ergonomic standards and methods used to evaluate this risks, limits from common assessment methods and age based changes that can increase risks at the particular activity.

	Energy expenditure	Postures	Action force	Load handling	Repetitive activities
Stan-dards		▪ EN 1005-4 ▪ ISO 11228	▪ EN 1005-3 ▪ DIN 33411-5	▪ EN 1005-2 ▪ ISO 11228/1-2	▪ EN 1005-5 ▪ ISO 11228-3
Asses-ment method	▪ Spitzer/Hettinger estimations ▪ Asfour, Jäger Garg calculation ▪ Chaffin + Herrin ▪ "Schwerarbeits-rechner" (A)	▪ QEC ▪ DGUV-240-460 ▪ AUVA CL (A) ▪ LHT (A) ▪ Ergo-Test ▪ RULA ▪ LUBA ▪ OWAS	▪ Bosch ▪ Bullinger ▪ Burandt ▪ Schultetus ▪ Monkras ▪ RULA ▪ Force atlas ▪ VDI + REFA	▪ Key indicator methods ▪ NIOSH ▪ REFA + VDI ▪ Siemens ▪ Schultenus ▪ Snook/Cirello ▪ FIOH • LHT (A) • MLT	▪ HAL-TVL ▪ LMM MAP ▪ OCRA • Strain index • OCRA CL • FIOH • HARM
Com-bined method	BAB/BDS	EAWS, IAD-BKB, ABA Tech, A-Flex, NPW, AWS light, AAWS, Check Age, ATS			
Limits	Light 4200 kJ Middle 4200-6300 kJ Hard 6300-8400 Very Hard >8400	Eg. EWAS <10 Points green 10-50 Points yellow >50 Points red	Eg. Force atlas Fi / Fimax <0,85 green 0,85 -1,2 yellow >1,2 red	Eg. KIM and MLT <10 Points green 10-50 Points yellow >50 Points red	E.g. KIM <10 Points green 10-50 Points yellow >50 Points red
Age-based change	Decline VO2-max, HR-max after 30 years of age. Total loss of about 50% till 65 years	Decline in flexibility of joints muscles and tendons, of about 30% between the age of 20-65 years	Decline in isometric strength by about 10% per decade	Decline in muscular force and power after age of 30 years. Total loss of about 25-30% till age of 65	Loss in reaction- and movement speed of 25% in the age of 18-65. Increased time for regeneration.

Figure 41: Overview of work stress, risk assessment methods, workplace limits and associated age-related changes [adapted from (Börner *et al.*, 2017, p. 10)]

For the assessment of physical stress limitations, one has to consider individual characteristics or workplaces including several stress types. Personal characteristics appear to drive a significant proportion of manual material handling (MMH) risk and should be considered when assessing it (Bagnara *et al.*, 2019, p. 559). However, ggenerally very few researches have considered personal features and capacities in assessment or planning of workplaces (Moussavi *et al.*, 2016, p. 420). There are a few approaches that already consider individual influences in maximum forces or maximum weights, but these approaches are mostly either not scientifically based or validated, or cover only topics too specific to be used in industry (Börner *et al.*, 2017, p. 10).

A usual problem in work assessment is the evaluation of inhomogeneous work stress, as most procedures consider work based on average values for weight, frequency, working positions etc. neglecting (average out) highly demanding subtasks (Schaub *et al.*, 2015a, p. 335). Therefore some methods have been developed that work based on weighted average values based on perceptual distribution of tasks for lifting in logistics (Walch, 2011), or based on algorithms (Waters *et al.*, 1993), but these methods do not consider individual anthropometric characteristics, or workers abilities.

Current developments in technology and socio-economic changes also pose significant challenges and changes for the ergonomic discipline and profession (Truxillo *et al.*, 2015, p. 369). According to EUOSH, 2013, pp. 27–30, PEROSH, 2012, p. 35 and PEROSH, 2016 the following research topics will be main challenges for the next decades

1. Demographic change, including topics such as sustainable employability to prolong working life, disability prevention and reintegration and psychosocial well-being in a sustainable working organisation
2. Globalization and the changing world of work – OSH research contribution to sustainable and inclusive growth, focusing on topics like multifactorial genesis of work-related musculoskeletal disorders, safety culture to prevent occupational accidents
3. OSH research for safe new technologies as a prerequisite for sustainable growth with its focus on new technologies as a field of action for OSH including digitalization (AR, VR, AI) and physical assistance including (HRC, Exoskeletons, etc.) (EUOSH, 2019a)
4. Research into new or increasing occupational exposures for the benefit of a smart and sustainable economy including main topics such as occupational risks related to newly engineered materials

In relation to **human work in industry 4.0** the literature analysis suggests that in the near future human presence in logistics and production is essential to compensate for technological limitations and to provide the most benefits for productivity, reliability, economy and flexibility (Gehrke *et al.*, 2015, pp. 1–28). The introduction of Industry 4.0 technologies implies significant changes of the production processes, and consequently of the work-tasks. The working environment and required employee skills and qualifications will also be significantly impacted by Industry 4.0 (World Economic Forum, 2016, pp. 20–22). Work 4.0 describes the ongoing efforts to adapt work to humans essential for production systems by the integration of assisting measures and technologies. By the integration of such assistance systems the qualitative changes will likely be positive for the workforce. Assisted workplaces offer new possibilities to keep elderly and ability limited workers in employment. Nevertheless, a very low number of such studies has been conducted so far, and scientific knowledge is lacking.

In studies, types of assistance were collected into a morphology of assistance and evaluated in terms of an ageing workforce. The focus was put on health and safety issues considering physical work stress, as this seems to be the most important issue for an ageing workforce. Based on this need for assistance, different assistance technologies where searched and summarized, and different technology clusters were assessed considering their benefits and limitations based on literature (see table 9). Based on the need for assistance and technological benefits a task-worker-technology-fit is crucial for successful implementation of suitable assistance. In this context the literature analysis showed that there is a major lack of knowledge for the physical domain. While there are models for the selection of information technology (Scherer *et al.*, 2007), robotics (Spillner, 2014) and general workplace improvements (Wittemann, 2017) taking into account individual factors, no generally applicable or technology independent procedure is available in literature.

After selecting and implementing assistance systems, the evaluation in terms of health related outcomes, impact on operational performance and the economic viability based on metrics described in section 2.5.9 is performed. Several metrics and areas of interest have been suggested in evaluating outcomes of assistance systems, but no holistic approach for the physical evaluation could have been identified from literature.

3.2 RESEARCH NEED

In terms of studies considering the elderly worker in their natural work environment, the conducted literature study revealed different research needs.

From a scientific point of view there is a need for longitudinal and cross sectional studies in companies that investigate and establish a cause-effect and dose-response relation of physical demands, age and resulting complaints, so called stress biographies (Bickelhaupt, 2010, p. 55; EUOSH, 2016b, pp. 85–86; Klussmann *et al.*, 2017b; Fraade-Blanar *et al.*, 2017). Even though such studies are cost and time consuming, only based on such results causal interpretations can be formed. As such studies are demanding in terms of the necessary research work, a close cooperation between practice and interdisciplinary researchers (e.g. gerontologists, industrial psychologists, physicians) is necessary (Sonntag, 2014, p. 55). Suggestion for the selection of the study designs and suitable methods of data collection can be found in (Lindwedel-Reime *et al.*, 2016).

For the area of workplace health promotion and MSD prevention, practicable procedures must be tested which are capable of providing objective access to stress and resource diagnostics at the workplace (Sonntag, 2014, p. 55; EUOSH, 2016b, p. 85). Considering health outcomes interventions must mediate physical stressors by applying ergonomic principles, the involvement of employees and employer commitment are seen as essential for a successful implementation. Although generic guidelines are available, no specific design, or practice for universal application can be identified from the existing scientific knowledge. Thus there is a need for a comprehensive and systematic research program considering effective interventions for workplace based health promotion and MSD prevention (Institute of Medicine, 2001, p. 437).

Further, there is a shift required from personal based to condition based intervention selection and application, as a considerable proportion of work-related illnesses are attributable to working conditions (Schlick *et al.*, 2010, pp. 756–757). Conditional approaches are often based on highly aggregated data on age and personnel structure forecasts, thus enabling a higher accuracy for prediction, but no individual solutions (Egbers, 2013, p. 55). Personal approaches are based on individual data, thus allowing specific solutions for the individual worker, but no prediction and generalization for other cases. Moreover, occupational ability and limitation assessment and documentation have no suitable formalization for interpretation and use by practitioners (Egbers, 2013, p. 85). Further, performance and ability limitations are described using a vast number of criteria, thus being resource demanding and cannot be satisfactorily predicted at individual level due to inadequate load-damage models (Reinhart *et al.*, 2009). Moreover, there is generally little research on the skills of production workers and no consistent approach for the collection and use of skills data in enterprises (Scheller et al. 2015, p. 138). This clearly indicates that a paradigm shift in research is needed and that new measurements have to be conducted in production systems to evaluate how functional capacities change with age in order to gain a better understanding of the age-productivity and stress dose-health profile according to different jobs and industrial sectors (Börsch-Supan and Weiss, 2016).

From a managerial point of view strategies, management approaches, and supporting management tools are missing. In literature there is a lack of information on how to match individual worker abilities with workplace design (Schlund *et al.*, 2018) and on key indicators in the fields of prevention and health promotion for an ageing workforce (Deml *et al.*, 2016, p. 439). This gap of knowledge negatively affects companies, as long as there are no suitable guidelines for the identification of age-sensitive risk in occupational health and safety management system (OHSMS). Thus, age-related data on production systems have to be collected and analyzed in industry to provide operation managers with adequate business models and business strategies. Therefore, future research efforts should make use of case- and field studies that rely on objective data and statistical analyses based on real and reliable data sets from industries. (Calzavara *et al.*, 2019).

Awareness and standardization are highly important issues for work design (Deml *et al.*, 2016, p. 434), but both are lacking in terms of age-related ability changes, age sensitive risks, age-appropriate workplace design and age-based worker assistance (Deml *et al.*, 2016, p. 434) (Varianou-Mikellidou *et al.*, 2019, p. 242). There are some useful tools in operation, but most of them have been developed before new technologies introduced new OHS risks and these tools need to updated in terms of policies, training procedures, work scheduling, ergonomics (Varianou-Mikellidou *et al.*, 2019, p. 242). Especially in the automotive sector some meaningful measures for preventive work design in face of an ageing workforce have been suggested, but to date no comprehensive process has been designed and awareness for the problems induced by ageing, and practical decision support models are lacking. As managing OHS in the context of an ageing workforce requires a holistic approach that takes into account the factors that influence the individual work ability (Varianou-Mikellidou *et al.*, 2019, p. 240), a comprehensive age management approach that merges data across different activity areas that considers abilities, stress and load histories is missing. (Deml *et al.*, 2016, p. 430)

Therefore, management processes tools have to be developed that include ageing workers' characteristics and consider the impact of the employment of older workers in their organizational frameworks, strategies, managerial tools to prevent, economic losses, productivity issues, brain drain and loss of institutional knowledge (Kumashiro, 2000; Abubakar and Wang, 2019).

From an ergonomic perspective overall, the analysis of the discussed ergonomic literature indicates that a strong focus is put on the ergonomic assessment phase in the design process, but the intervention phase is mainly neglected which means that most ergonomic intervention strategies are insufficiently linked to the problem to solve. Further, decision supporting process and tools for the ergonomic intervention process are missing (Brandl *et al.*, 2015, p. 2).

Although there are many scientific research results dealing with the demographic change, it is difficult to give specific suggestions for an age-differentiated work-system design (Keil and Spanner-Ulmer, 2012, p. 183). There is a consensus that especially elderly employees benefit from well-designed ergonomics and operational health services, and that the demographic change necessitates an adaption of the equipment, processes and assistive tools in assembly systems in order to compensate handicaps (Bauer *et al.*, 2018, p. 151). However, it needs to be stated that design suggestions for an age-based design of work systems is lacking (Keil and Spanner-Ulmer, 2012, p. 180).

In operations research a focus is being put on the implementation of age based performance restriction in planning and scheduling. But most macro-ergonomic planning approaches developed with a focus on ageing workforces also neglect individual employee skills, physiological capacity, ability limitations, and existing workplaces are currently being adapted reactively, to the specific requirements of employees with altered performance (Egbers, 2013, p. 20 p.53). This is often due to the fact that the awareness and knowledge needed for age-related planning is not available in industry. Since production planners in particular will have to deal intensively with an ageing workforce and employee skills, a corresponding qualification offer is missing (Scheller et al. 2015). In terms of awareness problems practical, learning factory based approaches as suggested by (Wolf *et al.*, 2019) could meet this requirements (Schenk *et al.*, 2014, p. 634), but associated research is missing. Concerning knowledge based problems concepts of capability databases as suggested by (Müglich *et al.*, 2015b; Müglich *et al.*, 2014), could be used as source of information of workplace design. Further, the link to suitable ergonomic interventions could be provide by extending the database concept by a catalogue of specific ergonomic measures, which the production planner can consider in case of skill bottlenecks (Scheller et al. 2015, p. 144), but a structured ergonomic intervention process is missing. Considering scheduling, the literature revealed a body of related research that includes different age based multipliers in line balancing, job scheduling and rotation, and resource assignment simulations (Calzavara *et al.*, 2019). However, most models are not validated, and the age profiles characteristics are not sufficiently emphasised (Calzavara *et al.*, 2019, p. 12). Research efforts focus on age-friendly balancing and scheduling models validation (Boenzi *et al.*, 2015; Botti *et al.*, 2017), and learning and forgetting models in relation to elderly workers. However, there is a lack of models and methods that consider the presence of supporting technologies and cooperating equipment during work (Calzavara *et al.*, 2019, p. 12).

In terms of ergonomic assessment of health related outcomes of work, more attention should be paid to the perceived health of elderly people, rather than to their diseases only (Tuomi *et al.*, 1997). For aging blue-collar workers it is recommended in literature to reduce physical work load with advancing age according to the normal age decline in physical capacity (20–25%) after the age of 45 years (Ilmarinen, 2001). Since existing work design and assessment approaches are oriented towards healthy employees, these suggestions are not methodically considered (Colombini and Occhipinti, 2006, p. 449), and employees who have lower ability levels based on age often suffer from physical overloading (Merkus *et al.*, 2019, p. 295).

Due to the increasing number of elderly workers and thereby decreasing physical abilities, it becomes necessary to adapt ergonomic assessment procedures for physical work to such issues. (Börner *et al.*, 2017, p. 10). However, an ergonomic approach for considering age-related performance changes in work assessment, and a relation of them with perceived strain and stress, is missing (Keil and Spanner-Ulmer, 2012, p. 179). There is no differentiated consideration of age-related factors in these procedures, so that there is a need for action, particularly with regard to the design of age-appropriate workplaces (Börner *et al.*, 2017, p. 10). Thus, ergonomic models incorporating personal characteristics into a comprehensive model are lacking (Bagnara *et al.*, 2019, p. 553; Barim *et al.*, 2019, p. 553). Further, there are almost no easy and holistic assessment methods that consider the factor age where applicable (Günthner *et al.*, 2014; Barim *et al.*, 2019, p. 553), but the repeated use of questionnaires for the subjective assessment of negative consequences of stress urgently need to be supplemented by more objective analysis instruments (Sonntag, 2014, p. 55). However, objective instruments and methods presenting tangible design suggestions for a systematic age-differentiated work-system design are missing in terms of physiological, anthropometric, organizational, physiological and informational aspects (Keil and Spanner-Ulmer, 2012, p. 178).

Therefore, researchers call for the development of age-differentiated risk assessment procedures, taking into account workforce diversity, including age-related changes and vulnerabilities in the existing assessment of occupational health and safety (Varianou-Mikellidou *et al.*, 2019, p. 240), and for screening methods for age-differentiated assessment of mechanical exposures that make age-related ergonomic deficits in work system design transparent, as well as for the development of age-differentiated ergonomic work design suggestions (Schlick *et al.*, 2013, p. 249). There are a few approaches that already consider age for maximum allowed forces or maximum weights, but these approaches are mostly either not scientifically based and validated, or cover only topics too specific to be used in industry (Börner *et al.*, 2017, p. 10). Further, there are almost no easy and holistic assessment methods that consider the factor age where applicable (Günthner *et al.*, 2014, p. 72; Barim *et al.*, 2019, p. 553).

Further research is needed in terms of methods that consider new technologies as physical assistance systems, augmented reality and VR, ergonomic simulation and age-oriented ergonomic assessment methods (Dahmen and Hefferle, 2018, p. 17; Calzavara *et al.*, 2019, p. 13).

According to the **adaption of workplaces by interventions,** findings from literature showed that the design of age-friendly workspaces by the efficient integration of Industry 4.0 solutions and collaborative or assisting equipment, is urgently needed to meet the individual needs of all users. In particular design guidelines and technical frameworks to support the creation of user-centred workspaces should be developed. (Calzavara *et al.*, 2019, p. 13) Even though this phase is at least as important as the ergonomic analysis as the latter only provides the base for corrective measures (Brandl *et al.*, 2016, p. 446). But research seems to completely neglecting the ergonomic intervention process as methodic assistance detached from ergonomic assessment methods or assistance for the ergonomic intervention process of working postures and material handling is basically not existent (Schlick and Trzcieliński, 2016, p. 446). Corrective measures are classified according to the TOP-model of occupational safety, making the ergonomic intervention process is a highly individual, knowledge-based process. Moreover, a methodical procedure or connection that derives ergonomic intervention of working postures and manual material handling based on ergonomic analysis has not be established. (Brandl *et al.*, 2015, p. 2) Current researches focus on minimizing the ergonomic risk and hazard, without sufficient consideration of workers' characteristics (Moussavi *et al.*, 2016, p. 420). Extensive analysis of the literature resulted in only one methodology that aims to derive workplace improvements based on individual worker abilities (Wittemann, 2017), and more research is needed in the areas of effectiveness of intervention and prevention measures, where especially high-quality workplace interventions are needed to improve the evidence base (EUOSH, 2016b, pp. 84–85). Due to the lack of methodological procedures an ergonomic intervention framework that clusters possible measures according to their benefits and can serve as a decision support for managers is to be derived.

In terms of **technology** development, implementation and their possible benefits for elderly workers the literature analysis revealed high hopes for improvement potentials, but a low degree of scientific based procedures and methodologies. Literature showed that especially for an ageing workforce physical assistance is of interest. Further, it can be concluded that there is a lack of knowledge concerning different technological solutions for improving workplace design (Fox *et al.*, 2019, p. 792). Thus a comprehensive overview of technology induced possibilities is missing. Moreover there is a lack of research considering potential positive and negative outcomes, resulting in a missing critical analysis of assistance (Fox *et al.*, 2019, p. 793; Mark *et al.*, 2019, p. 15). Thus, actual research on the effectiveness of interventions to support older workers is limited (Truxillo *et al.*, 2015, p. 369; Mark *et al.*, 2019, p. 15). Therefore, the design of an innovative, age-friendly and ergonomic workspace will become increasingly strategic requiring specific tools, guidelines and design standards for industrial application (Calzavara *et al.*, 2019, p. 13) The integration of IT and physical assisting technologies can help to create user friendly work places at affordable prices (EUOSH, 2019a; European Commission, 2015), but there is a lack of industrial use cases and application experience (Mark *et al.*, 2019, p. 15). Since some researchers also argue that several measures have been developed by a technology driven approach and due to a certain actionism, concepts and programmes should be subject to strict evaluation in terms of their effectiveness and suitability for older employees (Sonntag, 2014, p. 55).

Also within technology implementation the scientific base can be described as small and a clear lack of linking ergonomic measures and technological improvements to worker needs was identified (cf. Mark *et al.*, 2019, p. 15). One outstanding approach was found for human robot collaboration to link assisting benefits with worker needs, so that only low risk work places (green category in the traffic light system) remain (Spillner, 2014). But even here, more research is required and new criteria, models, and methods analyzing human–robot interactions and behaviors in a common workspace, with particular attention to ageing workers are needed (Calzavara *et al.*, 2019, p. 14). From the literature analysed it can be concluded that for low standardized dynamic physical work exoskeletons are best suited to provide the required flexibility and physical assistance. In such a scenario exoskeletons might be a suitable approach to counteract MSD (EUOSH, 2019b). They seem to be an appropriate measure for work stress improvements during manual handling tasks and awkward positions (Spada *et al.*, 2017; Theurel *et al.*, 2018; Fox *et al.*, 2019). But there still is the limited scientific evidence about long term health outputs (Schick, 2018) and a tremendous lack of practical experience. In summary, the safety and health hazards of exoskeletons can be estimated in some scenarios but not yet fully specified especially when it comes to long-term effects. As a result, there is still a need for comprehensive studies that take person-related, physiological, medical and biomechanical aspects of exoskeletons into account. (EUOSH, 2019b, p. 5) Moreover effects on productivity and workplace design are not researched yet (Fox *et al.*, 2019, p. 14). Further, the selection of an exoskeleton for a target application is usually done intuitively and there is no scientific procedure to relate exoskeletons to workplace based stress and worker needs (Weidner, 2016a). Thus, a decision procedure, is required to aid the selection of a suitable exoskeleton for a given application.

Last, with regard to the diagnosis of physical and mental effects of technical system implementation, experiments are often carried out that appear very artificial and reduce the complexity of the real environment. Thus, a transfer of results into practice is hardly reasonable (Sonntag, 2014, p. 55). The literature summarized here revealed different research gaps in the crossroad of elderly workers, workplace design and innovative assistance solutions as summarized in Figure 42.

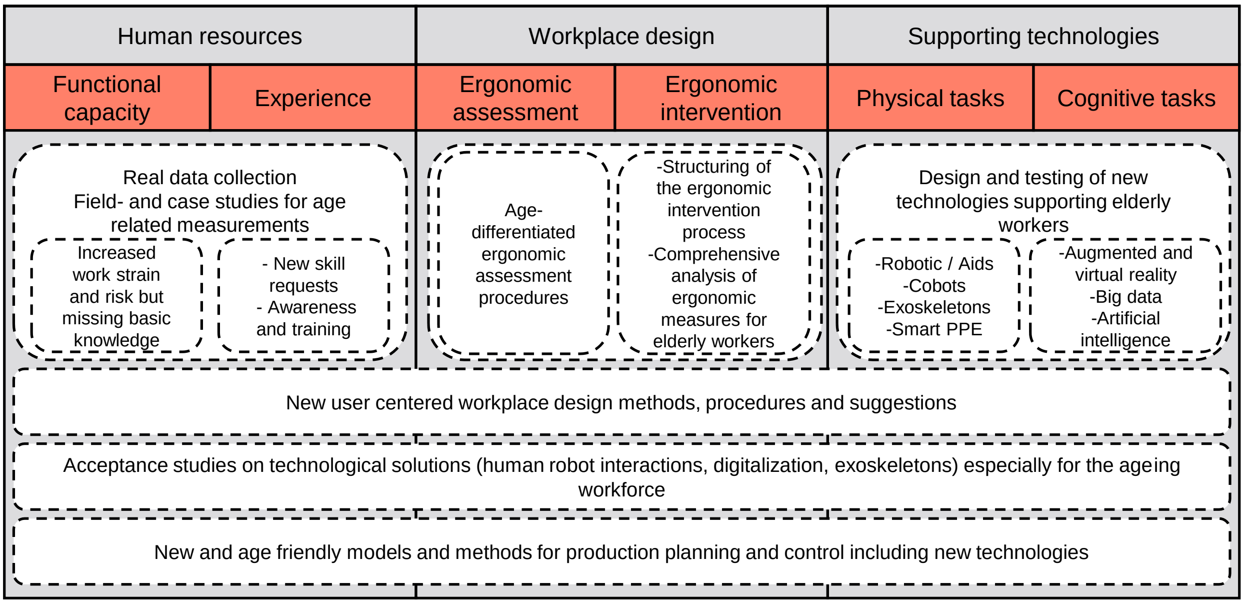


Figure 42: Identified need for research in the areas of human resources, workplace design and technologies

3.3 KEY STATEMENTS AND RESEARCH GAPS

The findings obtained from reviewing existing literature and existing process models can be summarized in the following key statements, that build the basis for the focus of this study. Based on key findings from literature the research questions will be formulated in the next chapter.

Lack of basic knowledge and uniform theories:

Present ergonomics standards concerning work are aimed at protecting an as wide as possible range of working population, but in practice they are aimed mainly at protecting only the healthy adult working population. It is fact that older workers whose physical abilities do not meet job demands face increased strain and injury risk and that work-related musculoskeletal disorders are more predominant in old workers. Based on a missing understanding of cause effect relations in health outcomes of occupational stress, most ergonomic assessment procedures are based on assumptions grounded in experience and have not been validated for their validity and reliability (Klussmann *et al.*, 2017b, 3,7). Further, ccurrent ergonomic assessment methods do not consider age-related changes of physical abilities. Therefore, an adaption of such methods considering age-related changes has to developed based on current methods.

- Need for action 1: Include the factor “age” in ergonomic assessment

There is no uniform theory of ageing, ergonomic intervention effectiveness, or physical work assistance that relates stress and strain considering age based performance alterations. A theory is missing that links the assisting need to stress and strain considering individual abilities and requirements of an ageing workers. Most ccurrent tools and procedures focus on an isolated reduction of work stress or a worker to workplace fit. The adaption of workplaces according to user needs is not considered systematically. The ergonomic intervention process is currently a highly individual, knowledge-based process without a methodical procedure. A methodical connection of the ergonomic analysis and the ergonomic intervention has not been established and methodic assistance for the ergonomic intervention process or technological requirements detached from ergonomic assessment methods is missing.

- Need for action 2: Structure the ergonomic intervention process

It is assumed that digital and physical assisting systems can reduce work strain and compensate for some age-related ability limitations, but no scientific methodological approach to identify suitable systems based on assistance need and work stress exists. There are several technology-driven developments within assistance systems for industrial applications. However, there are only a few practical examples of selection, implementation and assessment of such systems mainly in the automotive industry and there has not yet been a comprehensive general consideration of the possibilities of assistance systems for performance-changed employees, nor are there comprehensive overviews of specific technology clusters (e.g. exoskeletons). Moreover, there is no standard ergonomic assessment method for the evaluation of workplaces with implemented assistance systems.

- Need for action 3: Provide a comprehensive analysis of physical assistance and develop a concept for evaluation

Importance of industry-specific operational requirements:

Work stress and ergonomic assessment methods, as well as suitable ergonomic interventions are highly industry specific. While there are some meaningful approaches in highly standardized assembly line production, other industries lack such models, procedures and case examples. Further, existing models and framework often lack decision and implementation support, thus they are complicated to operationalize for practitioners.

- ➢ Need for action 4: Develop tools for practical application

According to the last key statement from literature, the investigation of the application context is key to be able to derive suitable solutions. Hence, findings from a field study conducted to derive the relevant industry specific needs for an age-differentiated procedure model will be presented in chapter 5.

3.4 RESEARCH QUESTIONS

According to the research need identified in the previous sections, the research questions are formulated as follows: The first and second research question (RQ1 and RQ2) are formulated in an explorative and descriptive manner. RQ1 is aimed at exploring factors that lead to problems for elderly workers at specific industrial workplaces and at an objective indication of a need for action. As quantifications of age-differentiated ability changes were identified in literature, RQ1 focuses on the identification of relevant skills and their use in work assessment:

RQ1: How to identify age-critical work places?

- What criteria have to be considered in an age-differentiated assessment of workplaces according to the companies studied?
- How to take into account general age-related changes quantified in literature, for an objective assessment of work requirements to identify age-critical work stress?
- How can an age-differentiated assessment of work conditions be used to build awareness for the need for assistance considering an ageing workforce?

Research question two is aimed at the systematic reduction of age-critical work stress with workplace redesign and of age critical work strain by the use of physical assisting systems. The aim of age-appropriate work design, besides a reduction of physical stress, must also include a regulation of work strain according to individual abilities. This means that the requirements must be designed in such a way that they do not exceed the individual abilities of the employee to avoid over straining. Therefore, RQ2 was formulated as:

RQ2: How to minimize relevant age-critical work strain by the use of physical assisting technologies

- How to identify suitable ergonomic interventions according to existing stress profiles in industry?
- Which age-critical work strain can be reduced by the use of physical assistance systems?
- How can a systematic procedure to align assisting technologies to workplace related stress and strain look like?

Research question three is formulated in a prescriptive manner. The answer to this question should highlight important practical considerations and give basic guidelines for age-based work design.

RQ3: How to manage a **systematic identification and reduction** of age-critical physical work stress and strain in industry?

- What steps have to be conducted to redesign work places in industry for a better fitting for elderly workers?
- How can this steps be operationalized for industrial practice?

3.5 INTENDED CONTRIBUTION

The study at hand aims to contribute to both, complementing existing knowledge and enhancing industrial practice. The main aim is to extend scientific literature by firstly adding new findings in terms of a new ergonomic assessment approach specifically considering elderly workers (RQ1) and second in terms of the structuring the ergonomic intervention process with a focus on physical assistance technologies (RQ2). Second, this research should also contribute to the existing knowledge of the ageing workforce in different industrial work settings by adding new empirical findings about related needs and problems. Third, the results of this study offer several benefits for the occupational practice. Managers and professionals from the area of occupational health and safety are provided with new methodologies and tools to counteract the demographic challenge. This seems to be of great importance as the review of existing literature did not reveal suitable methodologies, methods or tools for the problems faced in the study. The knowledge discipline to complement with this study can thus be specified as industrial engineering literature dealing with the design, commissioning, and improvement of integrated systems consisting of humans, materials, information, operating resources and energy (Martin-Vega, 2001, p. 1.10).

The intended contribution is a new conceptual model (RQ3) that enables the identification of age-critical work places and their adaption by technical assisting systems (see Figure 43). The creation of such a model has a mainly exploitive character and is therefore based on explorative investigations in industry.

Research questions	**Expected output**	**Expected result**
RQ1: How to **identify age-critical work places?**	▪ **Criteria for age-differentiated assessment** of workplaces ▪ Assessment method to identify age-critical work places ▪ Strain based **assistance need**	A process model that … …enables the assessment of work stress and strain and results in an assistance need …offers a structured process to compensate the differences between requirements and worker abilities by the use of assistance system
RQ2: How to **minimize** relevant age-critical work strain by the use of **physical assisting technologies?**	▪ **Evaluation method** to identify suitable **assisting technologies** based on the assistance need ▪ **Systematic procedure** to align assisting technologies to workplace related stress	
RQ3: How to manage a **systematic identification and reduction** of age-critical physical work stress with physical assistance systems in industry?	▪ Methodology, procedure and tools for industrial application	

Figure 43: Intended contribution of the study

4 METHODOLOGY

The following chapter describes the methodological approaches used in this thesis and the applied research process used. After the description of basic methodological considerations, a suitable research process for the problem is identified and described. On this basis, the method mix for clarifying the relevant research questions is derived and a research framework is developed.

4.1 GENERAL METHODOLOGICAL CONSIDERATIONS

A research approach describes the procedures and plans that are used to study a selected topic (Creswell, 2014, p. 3). Research in general can be divided into two types namely basic (theoretical) and applied (practical) approaches (Merriam and Tisdell, 2016, p. 3). While the purpose of basic research is to improve the general theoretical knowledge and understanding of the world, the aim in applied research is to help solving practical problems of the society (Roll-Hansen, 2017, p. 537). Thus, the aim of applied research is the investigation of the applicability of models and rules for academic-guided behaviour in practice, solving practical problems and enhancing practical decision making (Rossman and Rallis, 2012, p. 5). Further, a general distinction exist between research that systematically describes the characteristics of, or cause-effect relationships between events and phenomenons, and research that aims to discover the meaning of these phenomenons (Merriam and Tisdell, 2016, pp. 5–6). The first kind of research is labelled as quantitative research and the latter is summarized by the term qualitative research. While quantitative research methods often focus on testing hypotheses, qualitative methods are usually aimed at uncovering connections (Döring and Bortz, 2016, p. 184). The combination of qualitative and quantitative methods has become more and more common in recent years. The qualitative approach makes it possible to supplement aspects of quantitative and descriptive methods, which primarily deal with numerical abstraction, with verbalized interpretations (Merriam and Tisdell, 2016, p. 3). If a qualitative or quantitative approach alone is not appropriate in terms of solving a research problem, a combination of both can be used in a mixed method design (Döring and Bortz, 2016, p. 27). Methods from both areas can be combined in three different ways: either by embedding quantitative data in a qualitative survey (or vice-versa), by consolidating a qualitative and quantitative completed data set (triangulation), or by linking the data step by step (Creswell and Plano Clark, 2007, p. 7). Especially in applied research, where realistic and thus complex questions are the subject of interest, the importance and necessity of mixed method research designs is increasingly recognized (Näslund, 2002, p. 321; Golicic and Davis, 2012, p. 726). As different approaches are suitable for different topics, a careful selection based on important considerations has to be conducted. The underlying assumptions within this thesis deal with application-oriented or applied research.

4.1.1 Research process in applied research

Research projects that involve real companies go beyond single fields of science (e.g. economics), since the complexity of dealing with human work in industrial companies cannot be covered by a single theory (Heinen, 1991). The research field tackeled is based on a general understanding of the processes involved and focuses on solving practical problems, as such it can be considered as application-oriented. (Döring and Bortz, 2016, p. 185) System-theoretical considerations of industrial enterprises and the cause-effect relationships to be investigated in this context clearly show the interdisciplinary connection of knowledge and rules of different basic sciences involved. Thus, empirical research in this context must aim at the identification of practical problems and the examination of developed design approaches or proposed solutions in the specific application context, while also taking into account the relevant basic sciences (Ulrich, 2001, pp. 178–188). Accordingly, a one-sided use of methods to answer the research questions would contradict the complexity of the problem (Ulrich, 1981, p. 20), since application-oriented research always considers not only epistemological contents, but also the benefits for operational practice (Döring and Bortz, 2016, p. 185).

A research process that incooperates the interdisciplinary and complexity of this type of application-oriented research projects was introduced by Ulrich, 1981. This approach enables the selection of an adapted method mix of formal and basic sciences for complex practice-oriented questions with an interdisciplinary theoretical background, such as represented by the problem at hand. The research process is shown in Figure 44 and outlines the research steps to be conducted. These range from the identification and typification of practice-relevant problems, through identification and intepretation of relevant theories and hypotheses, to the development of new methodologies, including criterias, rules and models for the industrial environment, to their testing and implementation in practice.

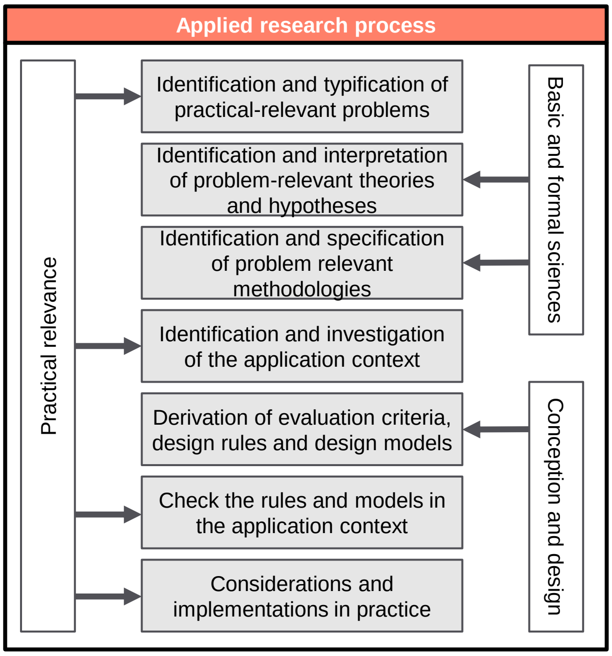


Figure 44: Applied research process [based on (Ulrich, 2001, p. 222)]

The task of age-appropriate work design in industrial blue-collar work activities represents an interdisciplinary topic. The research conducted represents a complex, interdisciplinary and application-oriented task, which, above all, contains engineering-, human factors-, and management science components and has a planning-preventive as well as an intervetive-reactive character. Accordingly, a thematic fit between the research process and the scope of research can be concluded.

4.2 RESEARCH DESIGN

In this thesis the approach of a field study was chosen to identify relevant influences from the managerial and operative point of view. Further, the identification of specific problems of elderly workers at certain workplaces and the adaption according to the specific needs is related to the operations perspective. Thus also for the identification of critical processes (RQ1) and their adaption by intervention measures (RQ2) and specific rules focusing on rational decision making are needed. On this level the detailed analysis of relevant changes in individual abilities and their influence on work performance is evaluated as they are necessary for the identification of relevant physical skills, based on declining abilities and worker’s subjective perception of related strain. The conducted research process to drive the process model is shown in Figure 45.

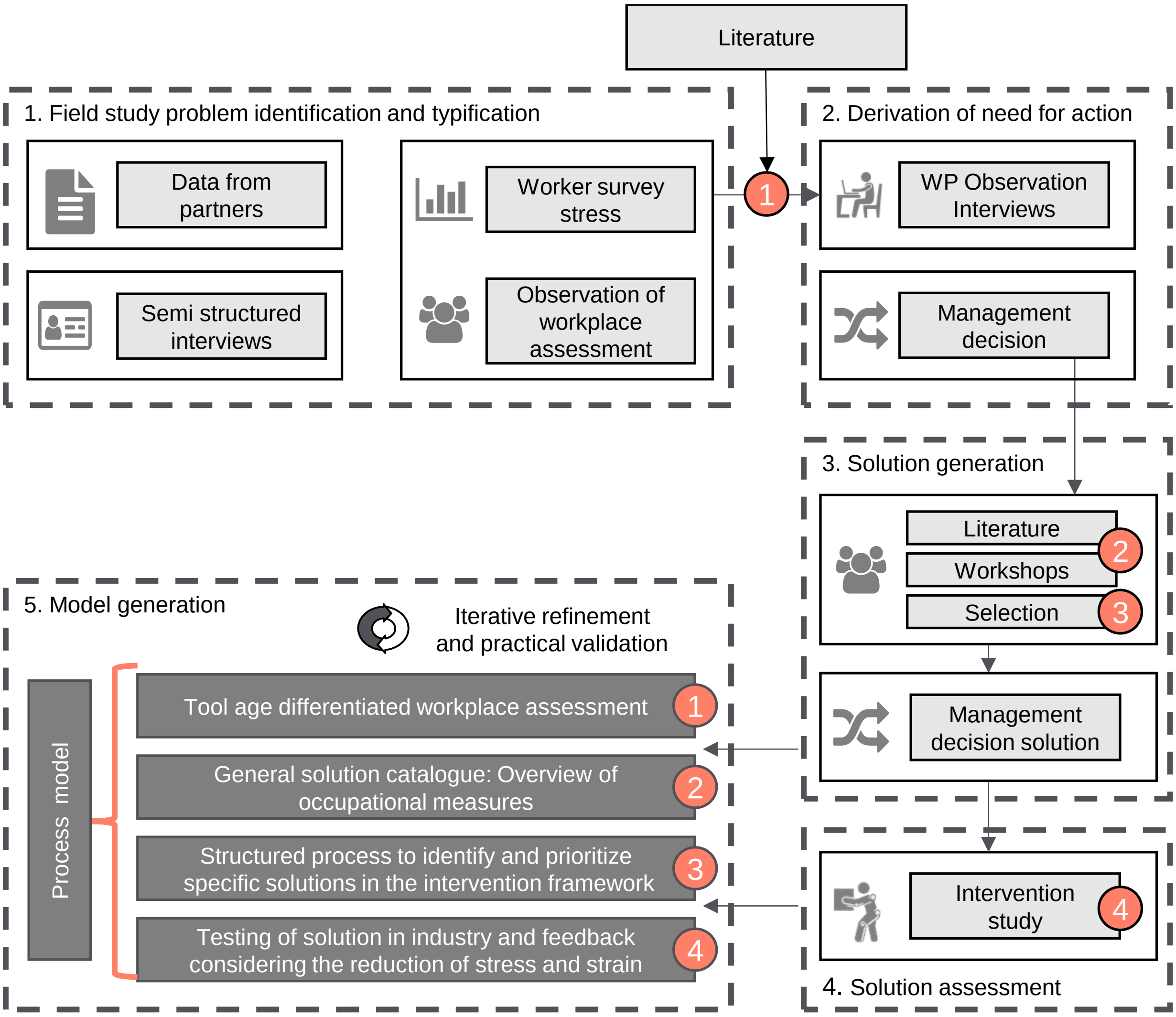


Figure 45: Steps conducted to develop the methodology showing the research activities in the boxes, and information flow with arrows

In this process, an initial empirical phase was conducted to geather a multitude of different qualitative data (interviews, survey results, observation reports, discussions and informal, as well as formal meeting notes) in a case-based method. This data was complemented with qualitative and quantitative data provided by the industry partners. This phase was aimed at determining the relevant problems in industry be means of explorative case reasearch within two companies, which are situated within the manufacturing and food retail industry.

In parallel a comprehensive literature analysis on the topics of health and ageing, human factors engineering and ergonomic work design, as well as on technological support possibilities was conducted to complement empirical findings. This was aimed at developing a basic understanding of the subject area and the relevant influencing factors, theories and methodologies in connection with the chosen types of work. Existing theories and methodologies in the fields of medical science, industrial engineering and human-factors engineering were gathered and tested/evaluated considering the feasability for the application context. In particular, physical abilities were identified that are important in industrial blue-collar work and existing knowledge on age-relevant changes of such activities were analyzed and summarized. In the following analysis, the summarized state of the art findings were supplemented with relevant challenges from practice. All this data was used to derive industrial requirements for age-differentiated workplace assessment and design and to modify existing ergonomic assessment methods, obtained from literature to fit the occupational requirements in terms of an ageing workforce (see number 1 in Figure 45). Based on the findings a methodology for age-differentiated workplace assessment and a tool for industrial application were developed based on abductive reasoning. The tool for age-related assessment was created by choosing suitable methods and extending them according to the needs from industrial practice (see section 2.4.3 and chapter 5).

In a second step the tool was applied in two different types of industrial companies. The application of the tool had two main goals: On the one hand, the tool was checked and iteratively improved in the application context according to Ulrich's applied research process. On the other hand, the results of the developed tool for age-differentiated workplace assessment were required as input for the following project phase. After identifying critical workplaces, and selecting the most relevant for the project within a management meeting, the second empirical phase started. This phase was aimed at exploring industry specific measures for age-appropriate work design and the role of physical assistance for such application. Based on a literature analysis considering potential benefits of occupational measures for elderly workers (see section 2.4.4), this phase was guided by the generation of solutions for practice, based on a participatory ergonomic improvement process (see number 2 in Figure 45). Several solutions were suggested by the researcher and generated and assessed by the workers. A selection process for feasable solutions in relation to the prevalent work stress was developed based on findings of the field study (number 3 in Figure 45). After a solution was chosen, a intervention study was carried out in both companies to evalute the benefits of the chosen solution in the real application context (number 4 in Figure 45).The methodology and tools developed were iteratively tested and improved during every step conducted. Finally the different tested, improved, and industry-verified tools, representing the building blocks of the systematic approach were combined to the process model enabling the indentification and reduction of age-critical work strain. The final sythetization of the single process steps and tools to a process model for industrial application complete the study design.

In summary the field study introduced here follows a multi-perspective approach. Firstly, the field study was intended to identify the industrial perspective in relation to the topic of an ageing workforce from the managerial and operative perspective (RQ1). This information is needed to later on derive suitable methodologies for mangers and suitable tools for improvement, fitting the requirements of practitioners (RQ2). Therefore, it is necessary to identify company-specific framing conditions, to be able to tailor the later developments to industry specific needs. As the data needed is strongly related to the natural environment of the individual company, field study research is necessary. The case companies were selected according to the project scope (see section1.4). Partner 1 is an international retail company. The divisions participating in the research project employ about 30.000 people in over 1200 stores, generating over 7 billion € of revenue in 2018. The main field of business comprises food retail involving typical work stresses from logistics work. In contrary partner 2 was chosen from the manufacturing industry. This partner is an international operating producer of firefighting trucks and equipment. At 16 international production facilities about 3.600 workers are employed. In 2018 roughly 900 million € of revenue were generated. The main field of business is the production of heavy machinery as trucks involving high physical work stresses and high postural loads due to product characteristics. Thus, two companies from different business sectors including different work tasks and stress were involved in the empirical study. However, the unit of analysis within the partner cases was carefully selected in order to ensure comparability, which is necessary in order to generalize the results and conclude from the particular case to the general class which a case belongs to (Gläser and Laudel, 2010, p. 96).

4.2.1 Research framework

A conceptual research framework is a graphical explanation of the central elements and expected connection of the research topic (Miles *et al.*, 2014, p. 20). A research framework is required for the structured collection and analysis of empirical data in field research as it illustrates the main factors, constructs, variables and their expected relationships. The developed research framework to guide the empirical data collection and analysis within this study is illustrated in Figure 46. It shows the physical workability as relation of the worker and the workplace. Related attributes are the stress on workplace level and strain on worker level. Influencing factors considered are effects of age and assisting systems on the workability. In RQ1 the relation of age on physical abilities and the increasing strain at constant stress is elaborated. As shown in chapter 2.3 the development of abilities with increasing age is mostly related to individual characteristics, but general tendencies were identified. On the one hand, statements on effects of such changes on work performance are often ability-related and not in relation to the work task (cf. general ability development in section 2.3.1). On the other hand, there are studies that provide tasks-related statements for concrete work situations (cf. ability-requirement comparison and worker-workplace-fit procedures in section 2.3.2). Accordingly, a generalisation for different work situations is not available. Due to the lack of transferability, it is difficult to define statements about the performance of operative workers, age-differentiated risk in relation to different work tasks and workplace design based on general decline of abilities (cf. Bruggmann, 2000, p. 25), or concrete data from the automotive industry (Wittemann, 2017, pp. 42–55), or logistics (Walch, 2011, pp. 59–70). Thus the explorative investigation of relevant skills and limitations in a field study is necessary. In RQ2 the reduction of strain with assisting systems is at the center of considerations. Here, almost no knowledge is available in literature concerning the reduction of strain related to work tasks that can be achieved with assisting technologies. Only a few practice examples show a strain reduction in specific body parts caused by exoskeletons in automotive industry. Hence, explorative investigations about technological implications in the real application context are needed. In RQ3 a structured procedure for levelling both factors is to be developed. Based on the theory of psychophysical scaling the reduction of strain achievable by assisting systems has to be evaluated and it should be investigated if it can serve to counterbalance the increasing strain through declining abilities in elderly workers.

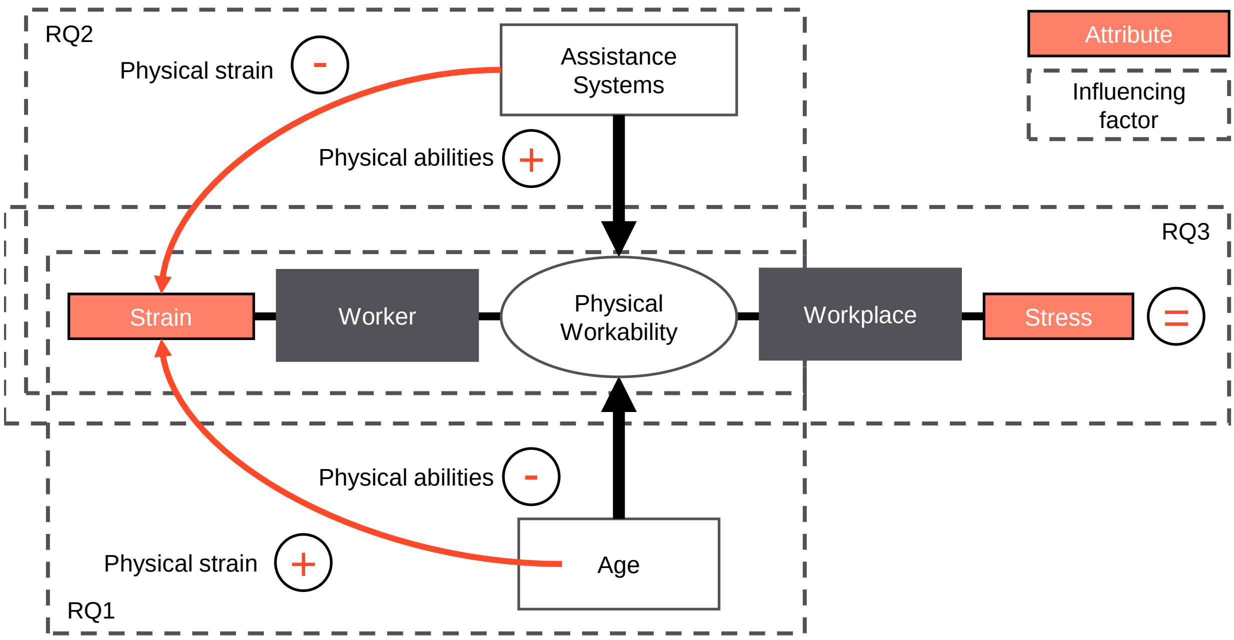


Figure 46: Research framework showing the content and connection of the research questions

The working model shows the assumed relations of associated terms. In this model it is expected that age negatively influences physical abilities and thus increases perceived strain. Moreover, it is indicated that assisting systems can lower strain by either increasing physical abilities, or reducing physical loading. Finally, it is assumed that by a refined ergonomic intervention process for physical assistance the strain can be managed to remain at a constant level with increasing age by the targeted use of assisting systems. Therefore, the experienced strain of elderly workers in industry and the effects of physical assistance technologies on it are the variable of main interest.

4.2.2 Methods used for data collection

As per (Eisenhardt, 1989, p. 534) the case study approach is particularly suitable to study real life problems and for the introduction of ergonomic measures in such settings (Lindwedel-Reime *et al.*, 2016, p. 55). Case studies can focus on a single case or a very small number of cases and usually include the collection of as much information as possible from a variety of media (interviews, documents, observations and audiovisual material) with a mixed method approach (Creswell and Plano Clark, 2007). The research design used in this thesis follows such a mixed methods approach, combining qualitative and quantitative research and including methods of both types of research. According to the research process the data collection follows an exploratory sequential mixed methods design, since this is a structured approach to analyze data in several sequential steps and allows data collection by one person in two or more consecutive stages in contrast to parallel approaches (Creswell, 2014, pp. 225–227). In addition, also the approach of data triangulation, referring to the merging of different data collected sequentially by different methods (Mangan *et al.*, 2004, p. 565), is performed in various surveys in industry. This case study was aimed at supplementing the existing knowledge with practice-relevant aspects and requirements from practice. In the case study, the knowledge gained from the literature analysis was compared with operational practice in the given context. Further, literature was complemented by empirical findings. In particular, deep insights into an existing workforce in connection with its existing loading situations were of interest. The case study analysis method is particularly suitable for this purpose, as it allows to analyse complex structures (Yin, 2018, p. 36) and its sequential design ensures that unexpected research results can be handled with great flexibility a high degree of clarity and traceability (Creswell and Plano Clark, 2007, pp. 86–88). The inductively gained findings were subsequently discussed in order to further develop and improve the model. The research approach chosen can therefore be described as inductive-confirmatory. Inductive means extrapolating from the particular to the general or from the concrete to the abstract (Döring and Bortz, 2016, p. 35). Confirmatory research aims at confirming existing hypothetic cause and effect relations (Fritz, 1995, p. 60). Wereas the confirmatory-instrumental approach according to Fritz 1995 puts the systematic verification of developed concepts at the center of considerations (Töpfer, 2010, p. 153).

4.2.2.1 Methods used to answer RQ1

In relation to **RQ1** the criteria for the assessment methodology were derived based on data triangulation of semi-structured interviews, different meeting notes, observations of company internal workplace assessments and statistical analysis of available company data.

Semi-structured interviews make use of a less formalized interview sheets, but use a list of questions to be asked that can be seen as an interview guide (Bryman and Bell, 2011, p. 467). This structure makes it possible to cover all important aspects and areas of a question, while at the same time retaining the narrative character (Döring and Bortz, 2016, pp. 372–374). The expert interview differs from the narrative interview in focusing on the opinions of experts within the researched context. For research in industry the employees of these institutions, such as managers or executives, can be considered as the relevant group of experts (Döring and Bortz, 2016, p. 376; Flick, 2008). Furthermore, different types of guideline interviews can be distinguished. While the focused interview is characterised by a stimulus or aspect whose effect is to be investigated, the problem-centred interview has a more hypothesis-generating character (Flick, 2008). However, qualitative interviews provide multiple opportunities for mutual discovery, understanding, reflection and explanation of practical correlations of the investigated field (Tracy, 2013, pp. 132–133)

Within this phase qualitative expert interviews were conducted with an interview guideline generated according to basic knowledge obtained from literature. Different main topics were defined according to age-differentiated assessment and improvement of work (see section research need 2.1.2). Within the main topics, a categorization of questions was conducted (e.g. “personnel based intervention” to classify measures for workplace design, or “KPI” for different statistics used measures the current state). This categorization was used for the structured analysis of interviewees’ responses. As the need for research differs for different groups of interview partners, guidelines were developed for four different levels. One guideline was developed for the conduction of interviews at management level. This guideline focused on the strategic perspective of an ageing workforce. Questions were directed towards the identification of the awareness of the topic (perception of and attitudes towards elderly workers in the company, consideration of the topic in strategic planning, conducted projects and initiatives etc.), related problems from management point of view (age-management and employment of elderly workers, HSE management, demographic change in the workforce, age and productivity –potentials and risks, economic aspects, involved departments, etc.), performance indicators in relation to the topic (Kugler *et al.*, 2016, p. 444) used for decision making (age structure, sick days, injuries, etc.), age-differentiated work design (conducted projects, active initiatives, need and fields for action, etc.), and the role of new technologies in relation to an ageing workforce (implications of digitalization, automation, assisting systems on work and the work system). Further, a questionnaire was developed for the target group of experts in industry for the topic of health and safety (e.g. occupational medicine/ health and safety officer, etc.). The questionnaire for this group had a stronger focus on the procedures to measure and manage stress and strain (methods and tools used, procedure of assessment, etc.) and related available results (health complaints, ability limitation statistics, identification of need for action, procedures for ability limited workers, etc.) and their implication for health and safety management (most important needs and areas for action, workplace redesign, conducted measures, etc.). The full interview guidelines for this two groups are provided in Apendix 1 and 2. Moreover, also the point of view of workers was considered to incorporate the operational perspective. The interview guidelines for the operational point of view comprised the groups of operational leaders (shift supervisors, production managers, store or division managers, production planners, team leaders, worker council, etc.) and blue-collar workers. Here, the questions were directed towards gaining insights in the operational perspective of demographic developments and focus was put on the identification of existing problems (health and safety in relation to older workers, performance and age, relevant abilities and related declines, relevant tasks that are stressful for older workers, etc.) and the identification of potential measures (practical solutions to deal with declining abilities in terms of team work, or individual assignment of workplaces or work tasks, coping strategies of older workers, workplace redesign, application of assisting technologies, etc.). The interview guide for this group is provided in Apendix 2. Based on initial findings from interviews an in-depth search with other beneficial sources of data was conducted. From worker perspective, a worker survey was set up to generate a more holistic picture on the topic at hand, most strenuous work tasks and diminishing abilities.

In a second step, another qualitative worker survey (Döring and Bortz, 2016, pp. 403–405) was conducted to identify problematic workplaces in terms of stressful work tasks and related physical problems and deepen the knowledge obtained in the interview study from a worker perspective. As the perception of the work stress by the individual worker is at the centre of interest, a semi standardized qualitative survey is a suitable method to generate in-depth information (Döring and Bortz, 2016, p. 403). The survey questionnaire was designed to match requirements on shop floor level (see Apendix 3). The first part includes questions considering a job description, socio-demographic workforce data, a description of the workflow per working day (activity, quantity and time), identification of relevant organisational implications (target times in relation to work content, tact frequency, tact binding, etc.). The second part was aimed at the identification of particularly stressful activities, provided support and assisting measures and specific measures for elderly workers. Finally, an overall subjective evaluation of the workplace and the working conditions was asked as open-ended questions. The survey was approved by the worker's council in both companies and issued by the team leaders to all workers in the area. The questionnaires were returned either via the works council, the team leaders, or directly by the workers to the author of this thesis, so that an unbiased answer to the questions is guaranteed.

In relation to the expert perspective, it was decided to conduct an observation interview in a workplace assessment on site. To gain better insights in the problems related to the issues in relation to ergonomic assessment methods and current tools an observation of a workplace inspection was conducted by the author of this thesis in both companies. This was aimed to identify shortcoming of the current procedures and in relation to the used tools. Therefore, the assessment was accompanied and the current procedure was qualitatively observed and documented, as this is a suitable tool to identify issues in the human-human interactions (Döring and Bortz, 2016, p. 333). A particular focus was put on challenges in data collection and existing challenges, problems and shortcomings of the current process or tools. The results were discussed after the assessment with the industrial experts in a focus group setting. Finally, due to the missing objectiveness in dealing with the topic on the industrial side, it was decided to conduct a deeper search in available data provided by the companies to generate reliable information and statistics for quantifying relevant challenges and problems.

4.2.2.2 Methods used to answer RQ2

In relation to **RQ2** an abductive reasoning approach has been chosen. To derive industry specific solutions tailord to practical needs a workshop series has been conduted in both companies. Based on the literature analysis conducted, solutions were generated in a participatory design with workers in a workshop series comprising 3 workshop for each company. Such participatory approaches are especially usefull in applied research were the result should provide a benefit for the industrial partner (Döring and Bortz, 2016, p. 1014; Szymanski, 2016, p. 155; Buxbaum-Conradi *et al.*, 2015). Within the 3 workshops, ergonomic assessment results were discussed, technical measures were developed and clustered and a solution catalogue of company specific problems and related measures was derived. Table 11 shows the setup of the workshop series conducted to derive industry specific solutions.

Table 11: Workshop series to identify suitable assisting measures

Workshop 1	Workshop 2	Workshop 3
Presentation and discussion of the age-related workplace assessment and comparison to workers perception Group work to determine the most strainfull tasks and related physical complaints Derivation of solution ideas related to T,O,P areas, by using a creativity enhancing method (brainwriting 6-3-5) Abstraction of specific ideas to solution clusters	Assessment of identified solution clusters in relation to the relevant work stresses using a pairwise comparison for work stress and a rating analysis of the utility of the derived solutions for stress- and strainfull activities Ranking of measure clusters according to their load-reliefe potential	Evaluation of identified solutions according to the introduced procedure Prioritization of solutions based on their potential

Between the workshops the data was analysed and findings from literature were incorporated in terms of a market analysis of feasible assisting technologies and their objective data of relief potential. All workshops were recorded audio-visually and analysed afterwards. Different types of prevention and intervention measures extracted from case research were analysed and summarized into general measure clusters. Thereafter, the clusters were categorized based on their classification as technical, organizational and personal measure. Further, a gap-analysis was carried out searching for highly stressing tasks in the worker survey and workshops and related solutions from literature. The generalized and categorized measures together build a general structure for occupational measures and the ergonomic intervention process that are meaningful in terms of physical stress reduction (general workforce) and strain reduction (specifically for an ageing workforce).

4.2.2.3 Methods used to answer RQ3

According to the systematic process for the identification and reduction of age-critical work stress, the testing procedure of the selected technologies for critical workplaces is necessary. According to the workshop results these technologies were exoskelettons for strain reduction for lifting and carrying activites, and the reduction of postural strain in the back. Five different available exoskeletons for this purpose were rented for industrial testing of the feasability in an intervention study.

A test protocoll and related questionnaires were developed and improved in a pre-test. The intervention study was conducted from Dezember 2019 to February 2020, including short testing of the technologies in real work environment. The approach of an ergonomic intervention study was chosen as it allows to evaluate the benefit of applying the measure in pre-post comparisons, where participants are examined before and after an intervention, as commonly used in practice-oriented research. This type of test design is known to be resource-efficient (Schnell *et al.*, 2014, pp. 215–238). For the prototypical application of the improvement process, an intervention study was conducted per company. After completing the workshop series the top three rated measures per company were suggested as interventions at a management meeting and the technology with the highest potential was selected.

Considering the test design, different criteria have to considered carefully, when planning the testing of an ergonomic intervention. As for age-differentiated design of working conditions, where the complexity of reality is the topic of interest, a qualitative approach based on a quasi-experimental field study setting is suitable (Döring and Bortz, 2016, p. 206). Taking into account the aspects for technology testing (section 2.5.11.2) to clarify the testing process, the investigation has to be carried out as a field study with a quasi-experimental repeated measurement design based on standardized questionnaires including the objective and perceived benefits of applying the intervention. However, the conducted assessment procedure includes only in-line testing at the specific work places in a field study. This is possible due to the fact that only market available solutions, already pretested in laboratory studies, were considered, as requested by the practice-oriented approach. Thus, the objective testing of physical parameters is neglected in the study, as it can be retrieved from laboratory studies in the related literature.

Based on the analysis of current studies and available questionnaire tools for assessing stress- and strain-related effects of interventions, a standardized assessment procedure, test design and a questionnaire set (PRE and POST) have been developed and pre-tested. The test design consists of two measurements, one without and one with the intervention in place. The testing time is set according to the tasks time, to keep the disturbances to work execution at a minimum and enable realistic task evaluation at a workplace. Workplace specifics in terms of weights, body postures and range of motion, task execution etc. are not controlled, but recorded to evaluate the task-measure fit. Therefore, the test design can be considered as tailored to the practice needs (see chapter 5). Further, the tests were designed so that they require low additional effort of the workers to participate and thus minimizing unwanted negative side effects. Table 12 shows the test design developed to answer RQ3.

Table 12: Intervention testing procedure

Duration [min]	Content
Min. 30	Execution of the relevant work task for acclimatization
10	General briefing and instruction and instruction in handling the body worn intervention, fitting of the device to worker’s individual characteristics
15	Explanation and conduction of the PRE questionnaire
30-120	Execution of the work with the intervention in place, and observation of confounding variables
15	Explanation and conduction of the POST questionnaire
	End

The subjective data collection methods include a self-assessment by means of several validated tools and observation as conducted in several similar studies (see sections 2.5.9 and 2.5.11.2).

The **pre-condition** questionnaire was aimed at the collection of data about age-specific health issues in relation to the work performed and an identification of related confounding variables. Therefore, it included accompanying questions for demographic and occupational data (based on “Nordic Questionnaire” (Kuorinka *et al.*, 1987)), the short version of the work ability index (Tuomi *et al.*, 1997), and an evaluation of the general stress and strain level at the workplaces according to the FEBA questionnaire (Slesina, 1987). The stress evaluation consists of 13 relevant items assessed by its occurrence on a four level scale and the strain ratings are assessed accordingly by a binary question. Also included is an assessment of state of health with parts of the “Nordic Questionnaire” (Kuorinka *et al.*, 1987). Moreover, the location and severity of physical complaints is assessed with a body map and the Borg CR 10 scale (Corlett and Bishop, 1976 Borg, 1998). The presence of complaints is assessed by six partly binary, partly scaled questions and the intensity of complaints is evaluated according to 20 body parts on a ten level scale. The perceived strain at the workplace as the main variable of interest is assessed according to different body parts and the different tasks based on the RPE scale (Borg, 1998). The strain ratings are specified for 20 body parts and the 13 items for ergonomic stress evaluation on the 14 grade RPE scale (cf. questionnaire PRE in Appendix 7).

The **post-questionnaire** aims at evaluating the effects of the intervention. The general perception of the system used, as a mediator for the evaluation, is evaluated with seven single item questions (based on the “System Usability Scale”) in relation to wearing time, perceived general reduction of strain, impacts on work execution, work time and wearing comfort. Further, the specific reduction of strain is evaluated for the same 13 tasks and 14 body posture by means of the same RPE scale. Finally, the perceived task-technology-fit is evaluated based on three items and the candidate’s intention to use the system is evaluated based on 3 questions. (cf. questionnaire POST in Appendix 8). Thus the evaluation enables the analysis of strain reduction according to the intervention used. In addition, observation can be conducted as an complementary method (Döring and Bortz, 2016, p. 328), to assure proper usage of the system and register confounding variables.

5 FINDINGS FROM THE FIELD STUDY

Based on the methodological considerations provided in chapter 4 this section discusses findings from the different steps conducted in the field study. Based on the empirical findings requirements and solution approaches are developed.

5.1 FINDINGS FROM CONDUCTED INTERVIEWS

To evaluate the industrial point of view on the topic at hand the collection of empirical interview data was conducted from July until October 2017. Within each company, a sampling considering different departments and workplaces was conducted according to type of work stress in the departments with the aim to interview a sample consisting of different occupations, jobs, tasks, stress types and requirements. This approach was chosen to identify most relevant job types where age-related changes play a major role. In total 37 interviews were conducted and 38 hours of audio material was recorded. As the aim of this study was to identify suitable important fields of age-based work design, age-critical factors at workplaces in the specific environment and age-relevant differences for ergonomic assessment, the evaluation was conducted according to the predefined categories. Therefore, the interviews were firstly screened and transcribed if meaningful information towards to topic was included. In a second step the responses were assigned to the predefined categories and a structured qualitative analysis was conducted.

5.1.1 Findings from interviews on management level

Seven interviews were conducted on management level with participants on CTO and CHRO level as well as in HR-management, and HSE-management. On average, interviews lasted for one hour and all topics in the guideline were discussed with all seven participants. Due to confidentiality in relation to the small sample of interviewees and the partially sensitive data, only aggregated results for both companies are provided in the following.

Interviews on management level showed that even though all participant knew about the demographic developments, there was low awareness for the topic in relation to the occupational needs deriving from it. Daily business is perceived as more important and human resource planning had their highest priority in dealing with a shortage of skilled workforce to be able to achieve the company's targets. Overall, older workers are seen as an asset for the company due to their experience and knowledge of internal procedures and work processes, products, etc. It is generally accepted that due to an increasing number of physical problems, their performance can be reduced. However, most managers think that the increasing number of physical complaints is stronger link to private reasons (sports, accidents, etc.), than to the working conditions. Further, analysis of the interview data also showed that both companies did not have a strategy in place to counteract the demographic change, nor conducted a future-oriented planning considering the ageing workforce. The consideration of age related problems takes place only in case-by-case management, whereas solution workplaces that still suit the changed ability profile are searched. It was also mentioned in both companies that there is a need for new strategies. One mentioned that they were reaching their limits, due to the fact that most “light duty” workplaces were already occupied by workers with physical complaints or limitations and it had been stated that there are different initiatives in place considering the aging workforce. The analysis of this initiatives showed that they are mainly related to operational health promotion on individual level (subsidies for and promotion of different types of sport activities). Further, both companies had projects by the Austrian initiative “Nestor Gold” in place that aimed for a certification as an age-friendly employer. In this initiative the areas of the individual, organization, culture and vitality are evaluated. This initiative strongly focuses on individual self-responsibility, organizational topics and leadership issues. Thus, there is no focus on workplace interventions and physical problems, or improvements are only partially considered.

With respect to related problems, the analysis of literature data on management level showed that physical impairment might lead to lower productivity and a higher share of sick leave in older workers. Both cases are considered to have a negative impact on overall productivity and economics and as the average age of the employees is expected to increase more rapidly in the next years, due to the demographic development and replacement problems the severity of the impact will worsen. Also, related problems are expected to become more severe as current coping strategies are reaching their limits. However, at this point in time, both companies did not have a broader strategy for dealing with this topic in place and no clear planning for HR and HSE areas to manage the problems could be named. As the departments that are involved in this topic, the human resource resort was identified as the leading division in both companies. Other involved departments included occupational medicine (individual problems, rehabilitation, worker workplace fit), worker’s council (support for workers with problems, planning and supervision of improvement projects, work place evaluation), health and safety responsible (workplace assessment and improvement) and work planning division (working conditions, realization of workplace improvements). However, efforts conducted in HR, HSE, work place evaluation and adaptation in both companies focus more on compliance with regulations and laws than on the worker needs. Worker problems were considered individually in micro-case management and in a reactive way only after limitations made the further execution of the current job impossible. Besides the affected worker, the worker’s council and occupational medicine are responsible for case management. Thus, most interventions were conducted after a longer sick leave and aimed at finding a new workplace for the ability-changed worker.

In relation to KPIs both HR division provided data about age structures but sick leave statistics were not available in aggregated format in both companies. One company was about to install an economically driven performance measurement system to consider reduced overall performance in workplace capacity planning. This procedure was aimed to consider reduced performance in planning of target times, so that performance limited workers are not considered as full manpower, similar to trainees and apprentices. However, this procedure was not specifically designed for age-related decline of performance, even if this was also considered as a feasible approach for the design of age-appropriate work. Further, no statistics of type and amount of ability limitations or tasks restrictions, no work-ability and no job-satisfaction scoring system and no fluctuation analysis are available in both companies.

Therefore, also in the area of work design no clear procedures, rules or strategies for age-appropriate workplaces re available. While ergonomic design of work was considered in both companies, several limitations were outlined according to economic aspects (work efficiency, time, financial input, etc.). Thus, while regulatory requirements are fully met in both companies, improved ergonomics is considered a secondary objective, which is only applicable if it does not contradict the economic objectives. Besides the general focus on physical aspects of work, no need or specific fields for action could be identified form results of the interviews on management level. Nevertheless, new technologies are considered to provide strong potential for improving ergonomics and age-appropriate work design, but knowledge what specifically can be achieved by means of technology is missing. Due to this, technologies are only considered as mean of productivity improvement and not in relation to ergonomic work design. Clearly, a holistic overview of related possibilities and benefits and clear rules for identification of suitable technologies in relation to worker limitations and workplace evaluation results would be beneficial.

Overall, on management level, it can be concluded that there is some knowledge about demographic topics, but a situational awareness of company specific problems is lacking. This is mostly due to missing evaluation of related KPIs, missing importance of the topic in comparison to daily business, missing resource allocation and missing aggregated data for a holistic consideration in management. As no data showing economical disadvantages or benefits of ergonomic work design and improvements are considered, the topic is only taken into consideration to the point of legal compliance. Thus, overall management awareness of problems, and need and fields for action can be considered as low, and decision making is not assisted by current procedures.

5.1.2 Findings from interviews on expert level

Ten interviews were recorded with experts in the field of industrial health and safety including occupational doctors, an occupational psychologist, worker's council members and safety officers. On average, interviews lasted 90 minutes and all topics in the guideline were discussed with all participants. Due to confidentiality in relation to the small sample and the sensitivity of data, only aggregated results for both companies are provided in the next section.

In relation to **methods and tools** for ergonomic risk assessment the evaluation of the material showed that both companies had a risk assessment and documentation in place to meet legal requirements. Also additional efforts in terms of ergonomic assessment s were taken by both companies but, the results of these efforts differed strongly. Both companies evaluated different workplaces by means of the key indicator method. In one company the evaluation was stopped after an initial evaluation phase, as according to the responsible person the method did not provide meaningful results. This is due to a low degree of standardization of the work tasks and a high rate of job rotation and several very different tasks being conducted by one worker. Further, the work tasks profile changes on daily and seasonal level. Due to the changing task profiles and multi-tasking work setup the key indicator method is perceived as unsuitable tool for the evaluation.

The second company, however, is still using an adapted evaluation based on the key indicator method. This is due to the fact that tools on checklist level do not provide information on an aggregated level needed for industrial workplace improvements and available screening tools do not meet industrial requirements. As a large variety of work stresses occurs in the company an assessment method tailored to specific needs was required. Therefore, the adaption of tools is conducted based on specific needs, by combining different evaluated assessment methods to one instrument. The created assessment method builds on the key indicator method for the evaluation of manual material handling activities, but extended the evaluation by an evaluation checklist for environmental influences (climate, noise, working in wet conditions), hazardous substances, general factors that increase work stress (time constraints, process binding, breaks) and the evaluation of specific worker groups in terms of pregnant woman and apprentices. Moreover, according to local legislation the working energy values were included in the evaluation, to identify heavy duty work places based on the energy expenditure. The working energy turnover is evaluated based on an estimation tool called "Schwerarbeitsrechner" (lit. heavy work calculator), where daily shares of different body postures in combination with physical exertion of work tasks are the input parameters to estimate the working expenditure. During the time the interviews were conducted, this company was re-evaluating all workplaces, as in the first evaluation the workplaces were evaluated without visiting the worker places. However, this procedure did not result in reliable values, so that the evaluation process had to be adapted including workplace visits and questioning of the relevant team leaders at the work stations. However, even after the process change, it was still perceived as very difficult to derive proper values for the key indicator methods, due to the subjective estimation of different body postures, weights and tasks conducted by every worker. In addition, the products produced were identified as a major challenge for workplace assessment, as most parts are manufactured in a fixed site production with highly varying durations ranging from a few weeks up to a few months. The low level of standardisation of this type of work therefore required a high degree of assumptions for job evaluations using the methods mentioned above.

As already indicated in management findings, the experts provided the information that the workplace assessment is mainly in place for the documentation required for legal compliance and for individual reintegration management after a longer sick leave. However, high risk values (red category in the traffic light system) were used as an indicator for general need for action of workplace adaptions. In terms of workplace redesign, this group emphasised the missing guidance for possible fields of action based on the evaluation results. In their opinion, a structured process and clear rules to follow in terms of high ergonomic risk rations would be desirable and a structured ergonomic intervention process was demanded by practitioners.

In relation to **workplace improvement** and an **ageing workforce**, the occupational medicin and worker's council members provided insights in relevant problems of elderly workers in both companies. However, due to missing data and aggregated statistics (accident statistics were only available on department level), only qualitative insights were provided. There exists consensus that the amount of cases where individual solutions are needed based on ability limitations is increasing and severe problems are in most cases attributable to elderly workers. Frequent problems of elderly workers were reported in relation to heavy manual material handling, followed by postural stress from frequent bending and twisting of the upper body, working in squatting, kneeling and lying positions, climbing of ladders, and generally overhead work. It was further emphasized that individual support is required for physically exhausting activities, especially for older workers. Moreover, the environmental condition, specifically working in hot and cold environments were named as age-relevant stressor. In contrary, action forces and repetitive manual material handling activities were perceived as not important risk factors in relation to the existing workloads in both companies. Representatives of both companies identified workplaces in the logistics department as highly affected in terms of physical work stress. This is due to the fact that work in logistics is rarely standardised and requires a high local flexibility and is thus complicated to support by mechanical working aids. In addition, such work often involves a high share of heavy loads and not ergonomically working postures where support is needed. Despite the fact that there are no special demands on hearing and vision in such occupations, both were named as age-relevant abilities. Nonetheless, the decrease in both sensory abilities can be compensated by simple means (visual aids, increased lighting, increase in contrast and sign seize, etc.). Most health issues were reported in relation to low back, knee and shoulder issues, and heavy lifting limitations but except for general advices, such as the reduction of overall workload and heavy lifting, extension of regeneration phases, or the avoidance of awkward body postures, no specific fields of action were identified during the interview. The subjective perception of working condition was identified as the most accurate indicator to identify an existing need for action. Further, the identification of need and field for action is based on the individual experience and knowledge of the parties involved and the improvement process for workplaces with high risk ratings is a very individual process, where the workplace has to be considered in detail including all relevant factors. AS a result, this process is very time consumingand due to the lack of a standardized procedure, structure and supporting tools the results cannot be transferred to other workplaces, increasing the time resources bound in this process. In terms of coping procedures for older workers, also the already identified approach of case by case management was confirmed by this group. The process includes an evaluation of remaining physical capacities after a long term sick leave and the search for a workplace with a suiting load profile. No projects where the workplace was adapted to the changed ability were reported. Current measures focus on worker based intervention, where the worker is advised to change their execution (i.e. lifting technique) of work according to workplace requirements. Further organizational aspects (layout, pieces per load carrier, partial retirement) were mentioned for intervention. Also, the company implemented several lifting aids at workplaces where heavy objects have to be manipulated. However, two problems were reported in connection to those which are a poor match of the aids and work specific requirements (local flexibility, usability, bad fitting to product specifications, etc.) and the increase in work execution time when using the system. Both issues lead to a low utilization of the aids by workers. In terms of technological assistance high potential was ascribed to individual support of workers in heavy manual material handling and solutions that enable individual adjusting of the workplace (i.e. height-adjustable) to prevent postural stress. However, technical solutions in terms of new technologies were not used in either company, due to missing knowledge and a lack of practical approach for the identification and implementation of suitable solutions.

Overall, on expert level, it can be concluded that the current process of workplace evaluation is perceived as complicated due to the specific requirement in relation to multi-tasking workplace, low degree of standardization of work tasks, and a missing fit between tools and industrial requirements. Tailored solutions are created by combining different assessment methods however, in this procedure, no overall assessment incorporating different risk factors to an overall risk value is achieved. Thus, no cross-workplace analysis is possible. This also implies that no structured prioritization of a need for action can be conducted, which is seen as a problem in relation to limited resources available. The individual case by case approach in workplace assessment is very time consuming, exacerbating the resource shortage. Thus, a structured procedure supporting the identification of the need for action and facilitating the identification for suitable solutions is highly demanded. Generally, a need for action is seen in both companies in relation to the demographic development and the increasing number of older workers. Considering the ageing workforce, there is an increase of cases where ability limited worker have to be (re)integrated and suitable workplaces are prohibitively hard to find in the current case by case approach. Thus, a method to calculate age-differentiated risks, to reduce the amount of cases by preventively indication problematic workplaces was perceived as very useful. Moreover, due to increasing demand, the adaption of workplaces to worker needs is perceived as important measure to increase the possibility to reintegrate workers. Age-specific assessment should especially include diminishing physical abilities and possible limitations to specific kinds of work stresses.

5.1.3 Findings from interviews on worker level

On worker level 20 interviews were conducted with blue-collar team leaders and workers. Interviews lasted for 45 minutes on average and the all topics in the guideline were discussed with all participants. Due to confidentiality in relation to the small sample and the sensitivity of data, onlyaggregated results for both companies are provided in the subsequent section.

In addition to a throughout confirmation of reported findings on management and expert level, interviews on worker level showed that several workers reported physical complaints of their own or of colleagues in their fields. The origin of the complaints was related almost equally to both, workload and private activities and injuries. Also a high share of interviewees in this group stated that they regularly leave work with pain in different body parts which they relate to the major type of physical stress of their workplace. Almost all workers perceived physical stress as the major factor the caused problems for higher age workers and for both companies several workers stated that according to the past and current physical work stress, their job could not be conducted by a person for the duration of an entire working life. A remarkable proportion indicated that they won’t be able to work until official retirement age according to their current physical state in relation to work requirements. With respect to relevant tasks and abilities, most notably several physical abilities relevant for work were mentioned as declining with age. These abilities included: physical endurance and strength in relation to material handling, decreasing physical flexibility and range of motion in relation to far reaching tasks and overhead work and limitations to work in strenuous body postures, sensory and fine motor skills in relation to manual work. In addition, environmental conditions were named as a stress factor, where age plays a major role. Based on the multitude of individual complaints reported and due to the low number of participants further exploration is necessary to derive a holistic picture. In terms of coping strategy individual experience was named as important factor. Conducting a job for several years enables the worker to lower work stress by knowing suitable techniques for work execution. A high amount of mechanical measures implemented by work place improvement projects conducted without involving the workers in the decision process, are perceived as simply irrelevant for the work. This is mostly due to a poor matching of the support provided to the support required by the work task. An additional perceived disadvantage of these solutions is that they prolong the duration of task execution, what leads to a not-use of the measure until to the point where physical limitation mandates its use. From the workers' point of view, mechanical solutions are often not practical in relation to the requirements at their workplaces and a participation of workforce representatives, conducting the relevant work task, is necessary in the intervention selection process. Also interviewees mentioned several individual supporting measures (bandages, shoe insoles, orthoses, etc.) which are also often personally procured and brought to work. Further, organizational measures (team work, division of work based on individual strengths and limitations, etc.) were reported as measures that are applied self-determined in the daily routine. Most measures perceived as helpful by the (older) workers can be classified as strain controlling and did not directly relate to work stress. In relation to the potential of individual assistance through technologies the result showed a split picture. On the one hand, workers were open minded and suggested different ideas what could be possible solutions, on the other hand several workers also showed a generally dismissive attitude towards the topic.

In conclusion, interviews on worker level showed a remarkable amount of complaints and limitations in contrast to statements from management and expert perspective, who advertised good working conditions. Based on the multitude of complaints, relevant tasks and measures reported by the workers, a survey of a larger sample is needed to arrive at a holistic picture of working conditions. Measures perceived as helpful were mostly strain modifiers, especially for the group of older workers but measures provided by the employer are often consider unsuitable from the workers' point of view. Further, the current selection process of intervention selection urgently needs to be changed to a process integrating the prospective users of the measure, to avoid the implementation of impractical solutions.

5.1.4 Conclusion of the interview study

The results of the interviews clearly showed that the experience gained during work life is an asset in complicated work task that require a highly qualified workforce. However, elderly workers are at high risk of not being able to perform at highest level due to physical impairments developed by stressful working conditions. Despite in general demand, in both companies no detailed ability limitation data about physical disorders or health impairments were available to prove this perception. It can be concluded that physical stress plays the dominant role for age-induced problems for the majority of the interviewed persons. The majority of managers, experts and workers surveyed identified a problem for older employees in relation to physical resilience, followed by problems in specific tasks as heavy lifting, and working in strenuous postures. Moreover, decreasing physical resilience is considered to be strongly related to many years of working in a highly stressful job. The statements made by managers, experts and workers in practice are in line with the typical changes in physical abilities with increasing age, as known from literature. All surveys show that physical strain is a particular problem for older employees due to their declining physical resilience. Both companies stated the need for action in work design in relation to the demographic developments and noted the missing consideration of older workers' ability profiles in workplace assessment, worker allocation and the improvement process. As physical stress in relation to material handling, postural work and environmental conditions were considered to be most relevant with respect to an ageing workforce, this types of stress have to be included in an age-differentiated assessment. It was discovered that current methods for ergonomic work evaluation, even though there were partially adapted to company needs, were perceived as complicated to conduct in relation to the specific requirements at work places in both companies. Thus, a new method tailored to the specific requirements could facilitate the evaluation and reduce the time spent for evaluation. In short, the method should be tailored to industry specific needs, should be easy to conduct, time efficient and provide age-based risk values. After identifying typical activities that can lead to age-related problems within the industry under consideration, the next step consisted of the conduction of a worker survey at workplaces including this type of stress.

5.1 FINDINGS OF THE WORKER SURVEY

The explorative worker survey was conducted throughout the different departments of both companies. Sampling considerations for the relevant departments were made based on the information obtained in the interviews. The survey was aimed to determine the most stress- and straining work tasks in the subjective perception of workers. Overall 90 workers participated in the survey. The average age of all participants was 41.6 years. Due to confidential agreements only aggregated results for both companies are described in the following.

Table 13: Overview of worker survey participants

Area	Department	Number of responses	Average age [years]
Logistics	Incoming goods and transport	10	47.7
	Order picking	9	43
	Finishing, packaging and shipping of products	13	45.5
Production	Manufacturing and machining	17	41.5
	Line assembly	10	29.4
	Fixed site assembly	15	37.7
Service	Shelf management	6	43.3
	Servicing customers	6	42.2
	Cash desk	4	52.5
Sum		90	41.6

The detailed responses enabled the derivation of a holistic picture of relevant work stress from the point of view of the current working population in the surveyed areas. For the **logistics related jobs** high stress work tasks identified in the survey consisted of heavy manual material handling tasks, working in bended, twisted and forced body postures, working most of the time in standing position, covering long distances per feet and climbing on stairs or ladders. The different jobs in the logistics department as listed in Table 13 did not show any remarkable differences in work stress. Overall logistics jobs were perceived as high stress jobs in relation to material handling and overall physical exertion by most participants. For **production related jobs** most stressful tasks included bended and twisted body postures and working in forced positions. While for machining tasks and line assembly, postural work was not perceived as a problem, heavy lifting and standing without rest over the whole workday were named as most straining activities. Special height adjustable fixtures and lifting aids were available for most machining and assembly workplaces, so that the workplaces were perceived as ergonomically designed in relation to material handling and body postures. In contrary, in fixed site assembly workers mainly named forced body postures i.e. working in lying and bended positions and a high share of working with ladders as the main topic. Manual material handling was not perceived as a problem as due to product weights and dimensions almost all material handling was conducted by means of cranes and lifting aids. Even though ergonomic experts provided working aids for working in forced positions, postural strain was still perceived as very high. A further improvement of the situation was not considered as feasible due to space constraints and product specifications. Overall jobs grouped in this category were perceived is medium to high stressful in relation to material handling and body postures. In workplaces grouped in the **service area**, tasks that were named in the survey to be most stressful included working in forced body postures and manual material handling tasks. In terms of relevant body postures working in squatting and kneeling positions and working on ladders and overhead height for prolonged periods were named most often as main stressor by workers from shelf management jobs. Further, manual material handling of heavy goods from overhead height was perceived as very stressful by the workers surveyed in such jobs. In the subgroup of customer service, the main stress derived from psychological stressors when dealing with customers. In relation to physical stress bended body postures, prolonged forced standing (customer service), and working in cold or hot environment were identified as relevant stress in this type of workplaces. Overall the physical exertion was perceived to be low in related tasks. Also in cash desk jobs, psychological strain was perceived as predominant stressor. In relation to body postures forced sitting in combination with repetitive manual work was identified as physical source of stress. Elderly workers were often named as better performing group in service jobs. Overall service jobs were perceived as less physically demanding. An exception exists in relation to shelf management jobs including high weights (e.g. beverage department), where task-stress-profiles resembled order picking jobs in the logistic area.

Overall, the worker survey in combination with insights from interviews provided a holistic picture of tasks that are subjectively very stressful for (elderly) workers. Further, activities that are perceived as most straining were identified per working area. This tasks are hence to be considered in a tailored age-differentiated workplace assessment tool. In addition, several ergonomic interventions, working aids and individual measures were named in the survey. This measures were considered in the gathering of possible ergonomic solutions (see section 7.3.3).

5.2 FINDINGS FROM THE OBSERVATION OF CURRENT WORKPLACE ASSESSMENT

To generate a better understanding of the issues in relation to current ergonomic assessment methods reported in interviews, an observation of a workplace inspection was conducted by the author of this thesis in both companies with the aim to identify shortcoming of the current procedures in relation to the used tools. In one company the assessment was conducted by a team of industrial experts which was accompanied at the assessment of the workplace and the evaluation procedure and its results, as well as issues in evaluation of stress were documented and discussed with the expert afterwards. In the other company, the inspection was carried out only by one health and safety officer, who was accompanied at his site visit. This inspection was aimed at identifying hazards at the location and updating legal documentation. The discussion of ergonomic assessment after the inspection confirmed information retrieved in interviews that the ergonomic assessment with the key indicator method did not fit industrial needs. Main issues were the derivation of average values for multitasking tasks where the main stress derives from postural work. The conclusion of this observation is that postural stress is a major requirement for a suitable assessment of ergonomic risks in this company. In addition, in the local warehouse and in tow other departments manual material handling was considered as stressful tasks as well which further requires the assessment of manual material handling. In this company, different worker surveys to evaluate psychological stressors had been conducted in the past. The results of these evaluations were discussed with the industrial expert. The survey did not focus on physical work stress but nevertheless the data revealed some useful information in relation to physical stressors. The results of the worker survey from the year 2013 included answers from 544 workers that clearly showed that lack of space was considered as a problem by 40% of the workers and about 22% felt strain caused by this factor. Similar bad ergonomic workplace design was a problem for 40% of the sample and 13% judged that as highly straining work factor. Finally, unfavourable work postures were named as a problem by 57% of the workers and 32% felt highly strained caused by that. Hence, this is direct evidence that especially working postures are a major problem for the workforce in this company.

In relation to ergonomic workplace assessment, results of the conducted workplace assessments with the key indicator method and the self-made checklist was provided. Related problems and shortcomings of the current evaluation are described in this section. The conducted observation revealed existing problems in the assessment of workplaces studied. These problems included no clear rules for the derivation of meaningful values for the assessment of low level of standardization in most workplaces. Problems were especially available in assessing task variation through either job rotation or long cycle times and mean values for very different loads. In addition, there were major issues in the compulsory assessment of working energy expenditure values with the tool “Schwerarbeitsrechner”, as observation of the workplace only covered a fraction of the total workflow. Therefore, most working postures and working operations had to be evaluated based on an estimation of average values by the workers. However, in the observation of the assessment, most workers did not know how to answer the question for an average weight or working posture for a specific tasks or load. Moreover, problems occurred during the observation of the assessment based on worker answers, where the information obtained could not be used in the assessment according to the KIM. This issues foremost exists in relation to body postures and movement, whereas both were often mentioned as one of the main stressors in relation to the tasks, the discussion of the identified issues showed that there were no clear rules to follow for the responsible person. Due to the lack of tools for postural assessment and lacking support to derive proper values for lowly standardized tasks, the existing problems in the workforce were known by the expert, but could not be assessed and therefore not communicated to or argued about on management level. Thus, it can be concluded that several problems exist in the current assessment procedures and tools in both companies. For a meaningful general ergonomic assessment and for the consideration of age-relevant issues a new tailored tool is needed, that is able to evaluate the existing work stresses and takes into consideration age-related changes in work strain.

5.3 FINDINGS FROM DATA OBTAINED FROM INDUSTRY PARTNERS

Different data provided by the companies was assessed considering age-relevant problems. This was done to generate a deeper insight in useful data sources that might be available in companies. Data sources that proved to give useful insights are summarized in Table 14 and explained briefly. In addition, relevant types of analysis and related finding are given. Findings of the data analysis that provided relevant information in relation to the topic at hand are highlighted in the subsequent section.

Table 14: Overview of meaningful data analysed and related findings

Nr.	Data	Conducted analyses	Findings
1	Employee list with information on age, time in the company, work schedule and allocated workplaces per department	Calculating the age structure Cross department comparison	Identification of on average old departments Need for action in relation to age
2	Aggregated or individual sick leave statistics on employee base	Group comparison for different age groups Comparison of different reasons for sick leave	Data for building awareness on the as-is situation Need for action according to health issues
3	Aggregated sick leave statistics on department area basis	Cross-department comparison normalized to age groups	Data for building awareness on the as-is situation Identification of problem areas for older workers based on sick days

Table 14 cont.: Overview of meaningful data analysed and related findings

Nr.	Data	Conducted analyses	Findings
4	Assessment of injuries and fatalities	Cross-department comparison	Building awareness on the as-is situation No data for age differences
5	Exit interviews in case of leaving the company	Descriptive statistics Pareto analysis Age group comparison	Reasons for leaving the job normalized to age
6	Other sources and documents that provide information on physical and mental stress in workplaces (Nestor Gold certification process, health promotion information, etc.)	Descriptive statistics according to age Content analysis	Overview of existing solutions for older people in the company
7	Results of the evaluation of mental stress by department and employee surveys	Comparison of different departments and age groups	Identifying of psychologically stressful areas Identification of some relevant physical implications
8	Ergonomic evaluation of workplaces	Ergonomic assessment with suitable tools	Identification of workplaces with high risk ratings

5.3.1 Age structure analysis

Further, aggregated data about sick leave days were provided for two departments with 6,218 and 3,655 employees, respectively. Figure 47 shows an age structure analysis and forecast for the next five years without replacements for a real worker population (n=6,218 workers).

The current age structure is very female dominated but quite balanced in age groups on female side. Only the group of workers older than 50 years is significantly smaller as the other groups. The age structure for males shows a youth dominated distribution (see Figure 47 left).

Figure 47: Current age structure (left) and 5-year forecast (right) without replacement (data provided by company)

The forecast for the next five years indicated that that the group of 50 plus year workers will slightly more than double for both, male and female workers. In relation to the sick leave statistics described in the previous section, this increases the importance of the topic of age-related work design even more for the department (see Figure 47 right). The analysis of age structures can be beneficial for identifying departments with a high average age or with a high increase rate of elderly workers. Thus it can serve to identify age-related need for actions.

5.3.2 Statistics of sick days

Company provided statistics of sick days of all 44,592 employees over the year 2018. The data were analysed according to the available age structure and age-related differences. Due to the sensibility of the data, only the number of sick days categorized by workers younger and older than 50 years was provided and no department comparison is possible. However, the comparison of elderly and younger workers revealed interesting insights. The data showed that 77.2% of the workforce was younger than 50 years and only 22.8% were older. However, 36% of lost days due to incapacity to work were attributed to the latter age group. While the average value of incapacity to work days is 10.2 days per worker and year over the total worker population there are remarkable differences for the two groups of workers. Comparing the age groups mentioned beforehand it became evident that for a worker younger than 50 years the average value is 8.4 days per year, while it is approximately twice as long (16.3 days) for a worker aged 50 or older. It can be concluded that in the available data about a quarter of the workforce employed causes over a third of all sick days and the average amount of sick days for the older group is double the amount of the younger group. This strongly implies a need for consideration of elderly workers as a special target group. Hence, statistics about incapacity of work days can provide meaningful insights if the elderly workers are faced with problems or not.

For two departments with similar work and load profiles, aggregated sick leave statistics were provided by one company. This data was analysed in a group comparison for different age groups and a comparison of different reasons for sick leave, as well as a cross-department comparison normalized to age groups. The descriptive statistic for department 1 includes 6,418 workers were 5,877 cases of sick leave were reported to the health insurance causing in total 68,754 sick days in the year 2018 (an average of 10.71 days per worker). From the data broken down in age groups presented in Table 15, it can be seen that the amount of cases per worker slightly declines with age but the duration per case drastically increase with age. An exception is the increasing number of cases in the 50 years and older group, however given the much smaller number of workers in this age group this might not be significant. As the increase in duration outweigh the decrease in cases, the overall sick leave per 100 workers more than triples from the youngest (<24 years) to the oldest (>55 years) age group. Generally, this tendency is in line with data reported in literature.

Table 15: Sick days statistics department 1

Age groups	Worker	Cases	Cases per 100 worker	Total sick days	Sick days per 100 worker	Sick days per case
until 24	1,693	1,741	102.8	12,251	723.6	7.0
25-34	1,451	1,439	99.2	13,419	924.8	9.3
35-44	1,335	1,075	80.5	14,556	1,090.3	13.5
45-54	1,401	1,153	82.3	18,169	1,296.9	15.8
>55 years	538	469	87.2	10,359	1,925.5	22.1
Overall	6,418	5,877		68,754		11.7

The descriptive statistic for department 2 (Table 16) includes 3,655 workers, where 3,025 cases were reported to the health insurance causing a total of 36,095 sick days in the year 2018 (11.93 days per worker). Similar to the previous data, there is a slight increase in cases per 100 workers, and the duration per case also increase with age in this sample, increasing approximately threefold from the youngest age group (6.8 days) to the oldest age group (21.1 days). Clearly the number sick days per case show a high correlation with age in both departments.

Table 16: Sick days statistics department 2

Age groups	Worker	Cases	Cases per 100 worker	Total sick days	Sick days per 100 worker	Sick days per case
until 24	1,136	774	86.1	5,286	465.3	6.8
25-34	797	645	80.9	6,451	809.4	10.0
35-44	673	594	88.3	7,251	1,077.4	12.2
45-54	768	750	97.7	11,569	1,506.4	15.4
>55 years	281	262	93.2	5,538	1,970.8	21.1
Overall	3,655	3,025		36,095		11.9

When interpreted independently, the data clearly provides the information that there is a need for action in preventing cases for elderly workers, since if cases happen in this group, they are on average more severe resulting in a longer time for recovery. A further interpretation of the data is possible when comparing it to an industry benchmark or benchmarking it against other statistics. Compared to overall Austrian statistics the younger groups are less sick than the average, but after the age of 35 the numbers are in line with reported numbers (see Table 17).

Table 17: Benchmark of sick leave days to official Austrian statistic (provided by health insurance)

	until 24 years	25 until 34	35 until 44	45 until 54	>55 years
Austria [amount]	1,203,0	1,031.7	1,093.0	1,412.8	2,137.4
Department 1 [in % of benchmark]	38%	78.5%	92%	101%	92%
Department 2 [in % of benchmark]	60%	89.6%	99.7%	91.2%	90.1%

A cross-department comparison shows that while sick days per case show the same trend in both departments, the amount of cases per 100 workers and age group is only slightly different. For sick days per case the duration linearly increases by the three fold from the youngest to the oldest worker group (see Figure 48 left). For the cases itself, in department1 the number is decreasing until the age group of up to 44 year olds and increasing afterwards. Department 2 shows a steady increase until the group of up to 54 year olds. Also for the oldest group, the development between the departments is inverted (see Figure 48 right).

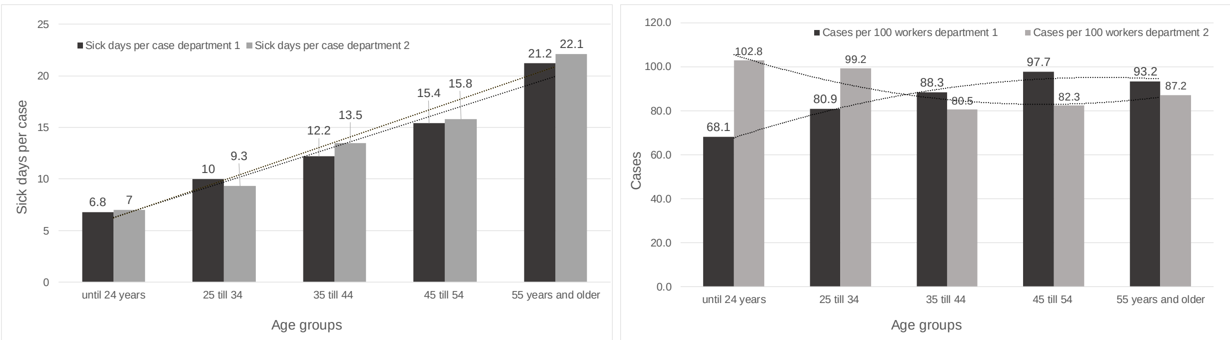


Figure 48: Comparison of sick leave days (left) and cases (right) per age group (data provided by company)

As the number of sick leave cases for categories of physical complaints like musculoskeletal disorders (MSD) is directly related to physical overload, this variance might indicate a different approach in relation to work environment, the physical work stress, or the handling of the ageing worker. Therefore, the differences should be analysed more in detail. Aggregated health data as provided by the health insurance can be analysed to identify relevant root causes as statistics with a classification of the reasons of sick leave according to the ICF classification (see section 2.5.8) can be requested at the health insurance. In Figure 49 the results of the classification of disease per case, age and ICF-classification are displayed. For the young age group, the categories of respiratory diseases and other diseases are the predominant reasons for sick leave. The category of respiratory diseases contains sick leave due to tonsillitis, bronchitis, influenza, flu-like symptoms and related issues. The category of other diseases includes issues like dizziness, general pain, nausea, headache and other such complaints. Only a very small share (4.5%) is related to MSD in this age group.

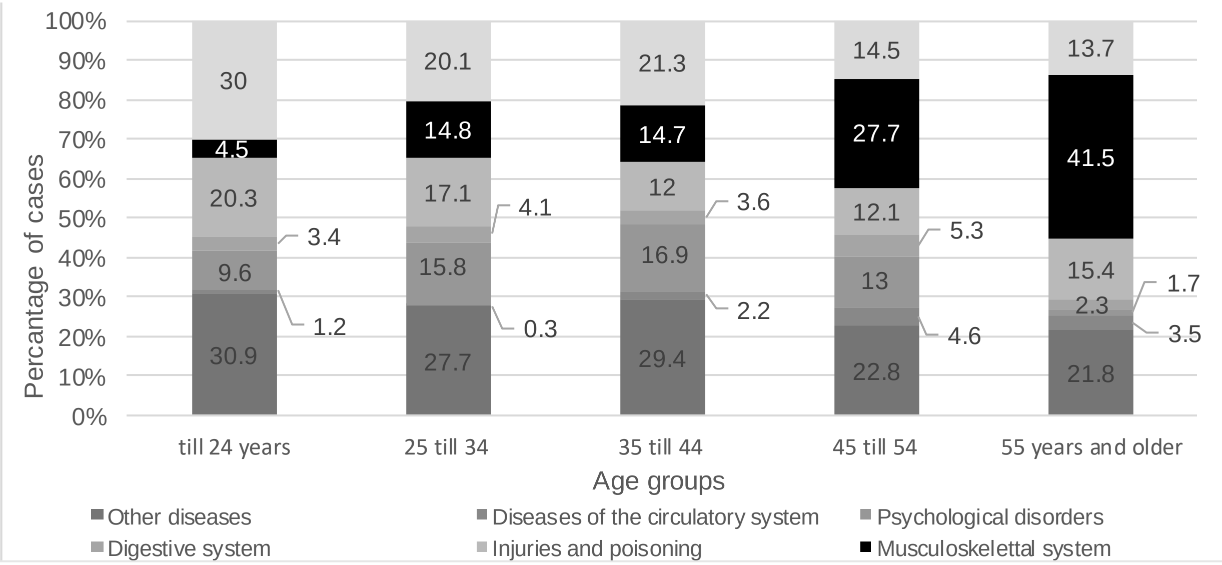


Figure 49: Classification of disease in department 1 showing a strong increase in MSD over age

According to Figure 49 this changes with increasing age. Most types of disease show a declining, or almost constant trend with age. Only the group of musculoskeletal disorders is increasing steadily with age, becoming the most recent reason for sick leaves after the age of 55 years, clearly making this type of disease the most relevant for elderly workers. Similar data were provided for department 2 (see Figure 50). Here, the percentage of cases caused by MSD steadily increases from 8.6% in the youngest to almost 40% in the oldest age group.

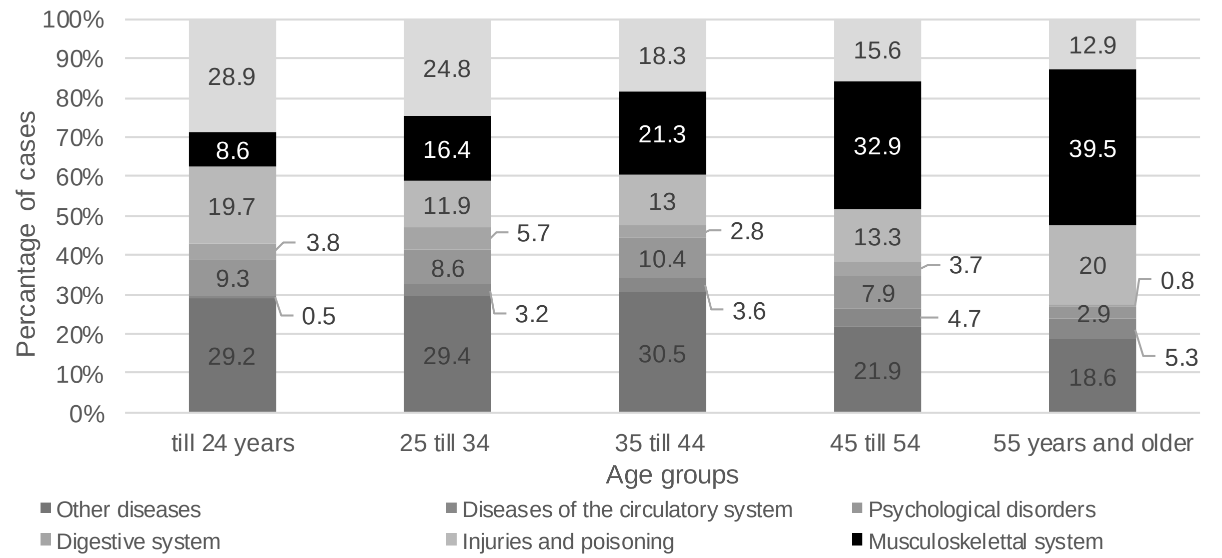


Figure 50 Classification of disease in department 2 showing a strong increase in MSD over age

It can be concluded that the analysis of sick leave days is a suitable KPI to build awareness for the problems of an elderly workforce. The analysis showed that especially the average sick days almost triple from the youngest to the oldest age group, while the cases per 100 workers don't show a general trend. Elderly workers in total have a similar, or slightly lower, number of cases of sick leave per 100 workers but are absent a significant higher share of working time, due to slower recovery. The increase in sick leave duration outweighs the amount of cases by far, so that the share of overall sick leave steadily increases in the older age groups. Comparing department differences can reveal a need and fields of action, specifically a cause analysis of sick leave statistics per department can support the understanding of these differences. In addition, the data discussed here clearly shows that for elderly workers MSD becomes the most important reason for sick leave and this might be related directly to longer recovery periods needed (see section 2.2.6). Therefore, prevention of physical overload that is significantly related to MSD must be considered a high priority in relation to the issues discovered in the present data set.

5.3.3 Interviews in case of leaving the company

One company also provided statistics about the reasons why workers were leaving the company ever year. This data source containing 3,117 interviews from the year 2017, showed interesting insights in potential problematic areas for the company. The results were post processed in a descriptive analysis and reasons for leave were aggregated to meaningful groups and analysed according to a Pareto analysis to identify most relevant reasons (see Figure 51).

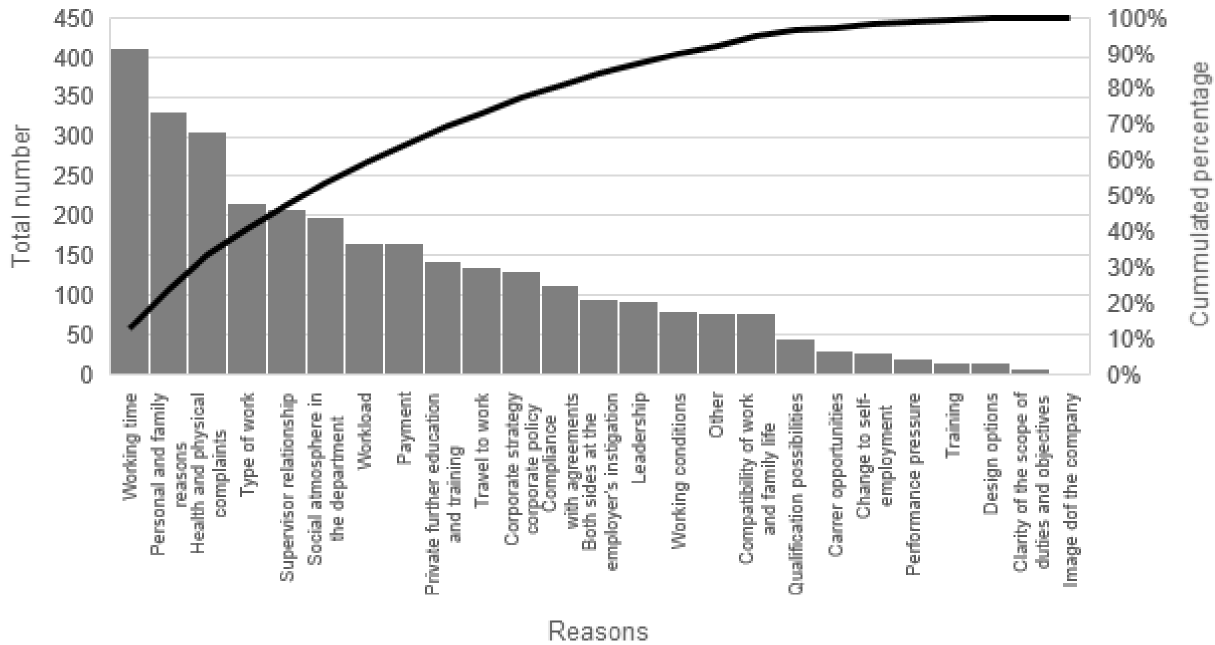


Figure 51: Pareto analysis of reasons for leaving the company. Data provided by the company partner.

Out of 25 reasons covered in the survey for leaving the company the categories with the largest share of responses included: working hours (13%), personal reasons (11%), health and physical reasons (10%), type of work (7%), relationship to supervisor (7%), working climate in the department/branch (6%), the workload (5%), the payment (5%). Thus, this data showed that the health status and physical reasons, as well as the experienced workload (physical and psychological) are main reasons to leave the job. In addition, the results were analysed normalized to different age groups. The comparison of different age groups revealed that while the type of work is the main reason for employees in the young age group to leave the company, very few older people leave the company because of that reasons. A quite contradictory picture was identified in relation to health and physical reasons as well as the workload. These become the main reasons for leaving the employer in higher age groups in service job with a lower physical workload (n=1,975) and in logistic work with a high physical workload (n=119) as illustrated in Figure 52 and Figure 53.

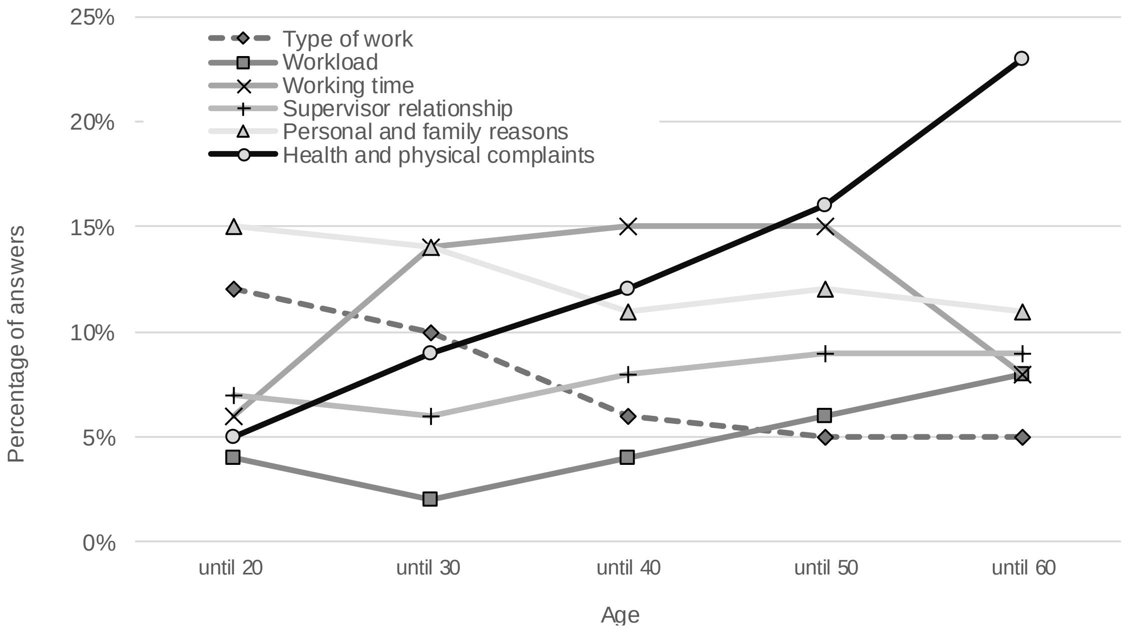


Figure 52: Reasons for leaving the job in service jobs with a lower physical workload.

For jobs with a lower overall physical stress level, data of the six most important reasons for leaving the company indicates that the type of work, and personal and family reasons are important motives for younger worker to leave their job. However, these reasons show a decline in importance with increasing age. In contrary, the workload and health and physical complaints are no important reasons for younger workers, but show a strongly increasing importance over age. Thus these factors can be considered as particularly age-relevant. As a third category, the working time is particularly relevant for the middle aged workers and only show a decreasing importance after the age of 50years. Lastly, the relation to the supervisor shows an almost linearly increasing trend over age, but is overall low.

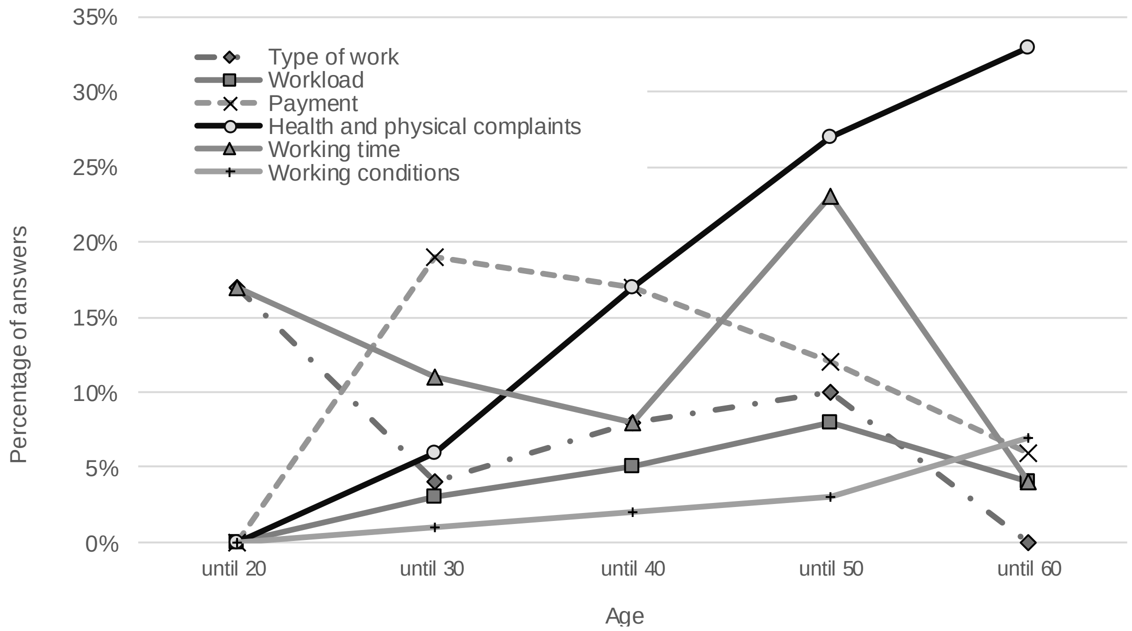


Figure 53: Reasons for leaving the job in logistic jobs with a high physical workload.

In occupations with higher physical demands similar trends were found. Health and physical complaints related reasons, the type of work and the workload showed the same developments over age as for service jobs. Instead of the supervisor relationship and personal reasons, the payment is an important reason why younger worker leave the job. On the contrary, for older workers, the working conditions (working in cold environments) is a highly important reason to leave to job. The working time showed no clear trend within this group. Thus for logistics jobs, health and physical complaints, the working conditions can be considered as especially relevant for elderly workers.

In conclusion exit interview data revealed that especially health and physical reasons in combination with the workload or working conditions cause elderly workers to leave their jobs. Overall the increase in health and physical complaints as a reason to leave to job stands out in comparison to all other reasons mentioned. Changing priorities of different age groups in relation to the job can be identified, which can be beneficial for age-differentiated work design.

5.4 DERIVED REQUIREMENTS FOR THE DEVELOPMENT OF A NEW SOLUTION

Synthesizing the findings from the different sources of data discussed in this section, the resulting requirements for the management procedure were summarized in Table 18. It shows the derived requirement in relation to the empiric source and outlines the possible solution to existing problems based on literature and industrial requirements (see Table 18).

Table 18: Summary of derived requirements

Phase	Requirement	Empirical base	Solution
Age-management	Raising awareness among management and workers about the challenges of ageing and the need for action.	Interviews Data analysis	The relevant data has to be identified and assessed to derive objective criteria. Objective decision support should be provided towards identification of need for action and possible fields of action based on assessment of different data sources
	Age issues have to be considered based on reliable data sources and KPIs.	Interviews	A procedure model guiding the identification and improvement of workplaces that provides reliable and clear support is needed
Assessment of age critical workplaces	New tool must build on current tools and available results. Assessment on checklist level is not suitable	Interviews, focus group on workplace assessment	KIM's are integrated, work environment evaluation can be transferred from existing data. The new tool also builds on speaking to the workers and incorporating their knowledge in assessment.
	Assessment must be holistic to include low level of standardization, job rotations and different tasks. Because of long tact times worker knowledge must be included in assessment.	Worker survey, Focus group on workplace assessment, workplace inspection	Procedure according to "Multiple-Lasten Tool" (MLT) for load handling and according to EAWS for body postures is included. Several tasks can be put into the form modelling the workday of a worker. These tasks should include most stressful tasks (high weight, time in awkward postures, etc.) but also different body movements to evaluate the WES.
	Assessment must include manual material handling of different loads	Worker survey, workplace inspection	Assessment procedure according to "Multiple-Lasten Tool" (MLT)
	Assessment must include assessment of working energy expenditure more structured and more precisely then current method	Focus group an workplace assessment and workplace inspection	Mathematical calculation of WES based on tables of "Spitzer and Hettinger (1959)" for body postures and material handling operations
	Assessment must differ in age for the included criteria. Differentiation should be on general level and not on specific ability level to stick to the methods currently used.	Expert interviews, interviews, focus group on workplace assessment	Age-related changes of abilities are modelled as mathematical functions and an aged based multiplier for the risk is derived based on the procedure according to ERGO-FWS assessment

Table 18 cont.: Summary of derived requirements

Phase	Requirement	Empirical base	Solution
Assessment of age critical workplaces	The time consumed for the assessment should not be extended	Focus group on workplace assessment Workplace inspection	Most time consuming task is the discussion after the workplace inspection to find suiting assumptions on feasible average values for the assessment and in terms of working energy turnover. Mathematical models make such a discussion obsolete. The worker survey sheet is a further measure to derive suitable values based on objective workplace data, shortening the time needed in talking to supervisors. Overall time needed for assessment stays about the same but data is more accurate
Assessment of age critical workplaces	Assessment should enable to put in specific remaining ability to identify workplaces for reintegration	Focus group on evaluation of assessment results	Multiplier for the age can be overridden by hand to put in the remaining ability as a percentage value in terms of force, Vo2_max, and postures. For detailed assessment of specific tasks or postures "ERGO FWS" assessment can be used on skill level
	Assessment excludes action forces and repetitive manual work	Worker Survey Interviews	Action forces and repetitive movements were not included as they were only existing at a limited amount of workplaces at one company respectively. Further, they were not perceived as predominant stress by the industrial partners.
Reduction of age-critical work stress	The physical domain is focused on	Interviews Survey Management decision	Physical work tasks of material handling and postural stress where considered as most important in interviews, the worker survey, and observation. Thus, they are preferred for improving work places. Environmental stresses are not considered.
	Individual and person oriented technical solutions are preferred measures	Interviews Management decision	Besides already available organisational solutions and a focus has to be put on individual technical solutions and strain controlling interventions
Identification of suitable solutions	Avoid unsuitable solutions	Interviews	To avoid unsuitable solution implementation a structured selection process is needed that include a rating of the solution in relation to the specific work tasks at the workplaces.
	Provide solutions that are highly used in long term perspective	Interviews	To avoid unsuitable solution implementation, the selection process must be a participatory process involving the workers at the certain work places. Further, usability aspects have to considered in the selection.

Based on the requirements an industry- and age-tailored tool has to be developed that incorporates findings from the different empirical findings from management, expert, and workers point of view. A methodology to develop such a tool is introduced in the next section.

6 Procedure model

In this section a structured management approach for the implementation of identified suitable measures is introduced. This process Is aimed at facilitating the introduction of improvements in industry for the practitioners. In this chapter the methodology to answer the research question 3 is outlined. The overall objective is to provide industrial companies with a step-by-step process methodology to identify ergonomic problems and adapt it with the use of technologies with a special focus on the age relevant strain component.

6.1 SYSTEM THEORY

Systems thinking is a generic approach helping to structure and interpret complex situations by thinking holistically and considering different perspectives (Züst, 2004, p. 34). These perspectives include an environment oriented, causal oriented, and structure oriented point of view (Haberfellner *et al.*, 2012, pp. 42–43). However, the main advantage of the systems theory is the ability to control the increasing number of system elements and complex interdependencies by reducing complex situations to controllable systems and subsystems. This makes systems-thinking a necessary skill in the modern industrial environment. (Pfeiffer, 1997, p. 17)

Production systems are defined as socio-technical systems that transform input (like e.g. human resources, know-how, material, or energy) into output (e.g. products, costs, and scrap-material) by means of value processes (e.g. manufacturing, assembly or transportation) (Nyhuis *et al.*, 2008, p. 20).Systemic, described as an interdisciplinary methodology that puts systems into the centre of considerations, is a suitable approach to deal with the topic at hand. Systemic combines contents of systems-theory, complexity research, ecology, economic theories, sociology and conflict-research, communications-theory as well as epistemology and action-theory. (Ninck et al. 2004, p. 6) Nick et al. developed a general systemic model including the four phases of opportunity- and problem-definition, problem-solving, implementation and use. Based on a throughout starting conditions analysis, suitable solutions can be generated in relation to real problems and not only symptoms. The result of this first phase is a detailed analysis of the current situation and the formulation of existing problems or challenges to tackle. In the problem solving -phase solutions are designed and examined regarding their ability to solve root problems whereas holistic solutions are preferable. To generate reliable statements of effects of the chosen solution the implementation- and use-phase provide insights in practical implications. The model is designed as a closed loop which means that the application of the model is continuously to be done. (Ninck, 2004, pp. 13)

In relation to age management system thinking as an adequate approach of to structure the approach including the different points of views of systems engineering. To deal with such interdisciplinary and complex systems, systemic is a suitable approach providing a general framework for procedure model generation.

6.2 MODEL THEORY

The practice focus of application oriented research, according to Ulrich focuses on supporting practical actions grounded in science (Ulrich, 1981, p. 10). Thus it is aimed at supporting decision makers in developing, evaluating and executing actions (Heinen, 1991, p. 11). Models are used to assist users to understand existing problems, by displaying the underlying cause-effect relations and pointing out information in regard to suitable interventions and can be distinguished in descriptive, explanatory, prognostic and decision models based on their character (Nyhuis *et al.*, 2008, p. 7). However, in research models are used for multiple purposes (Töllner, 2009, p. 8). Nevertheless, scientific models are always representations of natural or artificial relations that do only include the attributes of the original that seem relevant to those that build and use the model. (Stachowiak, 1973, pp. 131–133)

Within business studies mostly abstract-symbolic models are used that need fulfil the defined criteria (Schweitzer, 1997, p. 1). As management, according to (Drucker, 1986), is always aimed at economic profit, and modelling within business economics and engineering sciences is said to involve potential for increasing value creation in practical work (Holzmüllr and Bandow, 2009, p. 456), the main task of model creation in operations research is to develop and apply models for solving real decision problem (Domschke and Scholl, 2008, p. 1). Therefore, especially decision models, that support the evaluation of decision alternatives, by transferring the knowledge form explanatory models to clear rules for practical application (Nyhuis *et al.*, 2008, p. 7), are beneficial.

Hence, the model to be developed is aimed at representing the cause effect relation of aging and the related increase in work strain in ergonomic evaluations (explanatory), it only includes the relevant characteristics from the industrial point of view (application-orientation,) and is aimed at supporting the identification of suitable measures to conduct (decision-oriented).

6.3 PROCEDURE MODEL

To operationalize the system- and model-related approaches for industrial practice applicable, clear and simple methodologies are necessary. Therefore, building on renown methodologies from operations management is beneficial. Hammer 2019 summarized of seven common methodologies in the area for operations management. The number of steps varies between 4 (PDCA) and 10 (TQM) steps (Hammer, 2019, p. 121). In relation to improving the ergonomic situation at workplaces, process improvement methodologies, are needed. As a role model for the approach developed, a DMAIC (Define, identify, design, optimize, verify) process was chosen as structure methodology, as it is the industry accepted universal language of improvement processes (Burton, 2011, p. 53; Schmitt and Pfeifer, 2015, p. 51). However, in order to meet the context specific industrial requirements (see chapter 5) the phases were reframed and further detailed according to the empirical findings. The process and involved tools were developed in an iterative manner and inductive-deductive way, and refined according to industrial needsfeedback from application and testing. Figure 54 provides an overview of the developed procedure model and the fife steps defined as a result of the development process.

Process step	1 Define	2 Evaluate	3 Prioritize	4 Improve	5 Verify and control
	1.1 Definition of project structures 1.2 Definition of project roles and team	2.1 Evaluation of existing data 2.2 Analysis of age structure 2.3 Ergonomic assessment of workplaces 2.4 Evaluation of worker issues	3.1 Identification of need for action 3.2 Derivation of a need for action priority ranking 3.3 Definition of fields for action and associated measure clusters 3.4 Selection of feasible solution cluster	4.1 Development of measures – Generation of general solution – Preselection – Assessment of different solutions – Selection of a solution cluster – Identification of a specific measure 4.2 Preparation of implementation – Development of implement. plan – Preparation of the workforce	5.1 Implementation and conduction of tests 5.2 Assessment of impact and effectiveness 5.3 Development of a roll-out plan 5.4 Consolidation & documentation
Results Activities	➢ Project is clearly defined and roles are assigned	➢ Age structure analysis ➢ Ergonomic assessment ➢ Evaluation of worker perception and related issues	➢ Need for action in different areas ➢ Priority ranking of fields for action with measure clusters ➢ General solution cluster	➢ Prioritized solution propositions ➢ Implementation plan	➢ Verification of the solution ➢ Roll-out plan ➢ Documentation of benefits
Supporting tools		➢ Age-differentiated assessment tool	➢ Ergonomic intervention framework ➢ Solution priority matrix	➢ Structured improvement process	➢ Procedure and tool for evaluation of improvements

Figure 54: Process model for the identification of age critical work stress and its reduction by physical assistance

The first phase deals with a definition of scope and content of the project. The project strutures have to be set, the project team formed and available data should be prepared. The second phased deals with the evaluation of the as is situation and available indicators for interrelations of health issues, age and available workstress. Besides the derivation and evaluation of KPI’s based on avaiable data, a tailored tool for age-differentiated assessment of work, focusing on stress and strain was developped. Based on the findings and the analysed data, in step three the need for action is derived and related potential field for conducting measures are defined. The fourth pase is concerned with the improvement of the current situation by takling identified problems in the related fields of action. Therfore a concept for the generation of suitable measures focusing on stress and strain related issues with a special focus on physical assistance systems was developped. The last phase crromprises solution verification and ongoing control of ergonomic issues. Within this phase a evaluation procedure for physical assistance is introduced.

7 BUILDING BLOCKS OF THE PROCEDURE MODEL

In this chapter the scientific background and the approach developed to answer the research questions is described in detail. The overall objective is to develop a scientifically grounded step-by-step methodology that focus on industrial needs. For every phase or building block of the procedure, first, the specific knowledge from literature is summarized and the basic concept is derived based on existing knowledge. Further, the processes and tools developed are explained in detail.

7.1 STEP 1 - DEFINITION OF THE PROJECT

The first phase for all types of projects is a define-phase where the scope of the project and its framework has to be narrowed down. The aim of this phase is to determine the organisation and status of occupational health and safety, health management and health promotion initiatives. Therefore, an analysis of the organisation (e.g. values and culture), of occupational health and safety roles, tasks and actors (e.g. occupational safety specialists, company doctors, works councils), as well as of existing activities and measures (e.g. scope and timelines of risk assessment) is necessary. As HSE management is a holistic task, roles and knowledge might be spread over several departments. Therefore, gathering all available data might be a resource intensive task. Based on experience from industry, semi-standardized interviews and worker surveys are suitable means to identify relevant stakeholders and complement the missing relevant information.

7.1.1 Define structures and prepare relevant data

As mentioned before, HSE management is a holistic task and involves several professionals from different fields of knowledge. Based on a review of different projects concerned with workplace design for an ageing workforce and the project committees in the industrial partner companies, critical project structures, roles and teams can be identified.

Generally projects within organizations are defined by their attributes of importance, performance, life cycle, interdependencies, uniqueness, resources and conflicts (Meredith *et al.*, 2018, pp. 9–11). Pre-conditions for a successful project executions are a clear problem statement, promotors for the topic at hand, clear and accepted project goals, a defined project plan including major tasks and resources needed and defined project structures and organisation (Patzak and Rattay, 2009, pp. 15–129). Therefore, in the define-phase, these preconditions must be clearly set for the project. Problem statements can be derived based on existing data, internal evaluation results, or worker perception and complaints. Clear goals have to be formulated which should be specific, measurable, achievable, reasonable and time-bound (Doran, 1981). Improvement projects in industry usually follow the typical define, measure, analyse, improve and control (DIDOV) cycles (Meran *et al.*, 2012, p. 10; Schmitt and Pfeifer, 2015, p. 76). Therefrom, a project plan can be derived and resources can be planned.

Besides general project management issues, specifics of HSE and age management projects are explained in detail in the following paragraph. Such projects generally involve objective data-based information in the areas of human resource management and operations management and perceived subjective information from the worker’s point of view. As stated in the research aim, the goal of the developed approach is to identify and minimize age-critical work stress. Therefore, the project structures have to be defined accordingly to set up the possibilities to collect and analyse these types of data and provide available resources for needed work improvements. Based on the conducted field study the following information can be beneficial for the project and should be prepared in the define phase:

Company internal statics:

- Statistics of **sick leave** can serve as an indicator to identify problem department, areas or workplaces, based on numbers and reasons for sick leave. Statistics of reasons for sick leaves are usually not available at specific companies, but can be obtained at local health insurance companies, for a detailed assessment of sick leaves statistics. A statistics of the **age structure** of different departures can be used to identify departments with inhomogeneous groups of workers. The development of the age average for the department can be compared over several years to derive a need for action in terms of replacement or retiring strategies. Groups with a high amount of elderly workers or a high average worker age can be put in the focus of further considerations, or workplaces with only young operators can be excluded from age-differentiated analysis (for an exemplary evaluation of such data see section 5.3, for an age structure analysis refer to available tools).
- Statistics of **worker's ability limitations** can offer further information about special issues to consider. For a procedure to analyse such data refer to (Wittemann, 2017, pp. 44–61) and (Walch, 2011, 60-64) and for in relation to workplace improvement and preventive planning see (Spillner, 2014, pp. 112–118) and (Wittemann, 2017, pp. 85–98) .

Different types of workplace evaluations and improvements

- **Hazard and risk assessments** are available in every company, as required by legal regulations. However, scope and level of detail can differ widely between companies, as shown in section 2.4.3. Therefore, in the define phase all types of hazard, ergonomic risk and psychological evaluations of workplaces conducted by the company or external consultants should be gathered. Important data of workplace evaluation include task descriptions, workplace stress heat-maps, hazard evaluations, measurements of environmental conditions and hazardous substances, worker surveys of physical, social and mental stress and strain (see Szymanski, 2016, p. 158). Other data that might be useful for a holistic analysis include accident statistics, occupational health care measures and documents, qualification profiles and requirements
- Further, already **implemented measures** for improving workplaces and occupational health promotion as well as related evaluations of the impact and effectiveness should be gathered and structured. They can serve later on as a starting point for deriving new measures, or can be implemented in an ergonomic best-practice database for company wide use.

Other potentially meaningful data:

- Some companies conduct **interviews in case of leaving the company**. Also from standardized interviews meaningful data can be excluded to identify relevant problems within the worker population. Also comparing younger and older workers can reveal problems of specific group of workers (see section 5.3).

7.1.2 Define and assign roles and responsibilities

Key knowledge required for the execution of the project involves business knowledge of structures and responsibilities, human resource department related knowledge of employee structure and regulations, medical knowledge about worker abilities and limitations and work system related knowledge about work tasks and related work stress. Therefore, key roles involved in the approach are defined as follows:

- **Management representative** – initiated the project, defines goals, allocates resources and is responsible for the overall project success. Final instance for decisions and allocation of resources. In terms of HSE topics mostly a leader of the human resource department as e.g. the chief human resource officer (CHRO). For workplace and work system improvement a high representative from operations area e.g. the chief technical officer (CTO).

- **Human resource management specialist** – holder of relevant statistics in terms of employee structure, age structure, persons with impairments, etc. Especially important in the early project phase to identify problems. Typical role HR employee.
- **Workplace health promotion specialist** – responsible for occupational health promotion and holder of information of already implemented measures in terms of occupational health promotion measures as healthy food, sports subsidy etc. Important to identify existing and implement new accompanying measures. Typical role HR employee.
- **Worker representatives** – in charge of several legal topics concerning all types of measuring recording and assessing worker related information and involved in most work improvement projects. Knows about problems from workers point of view and worker specific complaints in terms of ability limitations, reintegration, rehabilitation etc. Important for the approval of acquisition of data and testing of new solutions. Typically, a representative from worker council and representatives of special groups of workers (e.g. impaired workers)
- **Work design specialist** – responsible for the design and improvement of work system, work tasks and work places and therefore also responsible for the resulting work stresses. Often holds information of successful and failed workplace improvements. Important for the improvement of workplaces. Typical roles include work system-, and work planner.
- **Occupational medicine specialist** - responsible for scientific support during the project. Can provide information about health related issues at workplaces and about worker limitations. Mostly included in worker reintegration and back to work interventions. Relevant for the assessment of stress, strain and the effects of intervention. Typical role occupational physician.
- **Occupational health and safety specialist** – responsible for hazard identification and ergonomic workplace assessment. Can provide relevant information about workplace assessment results and effect of interventions implemented. Typical role safety officer.
- **Work place specialists** – can provide information about work stress and work strain, work processes, and the execution of work (often not in line with documented rules). Has the best knowledge about improvements required for a specific workplace and often provide ideas how to improve the workplaces. Important in the improvement of workplaces. Typical roles include group leaders and workers.
- **“Age manager” –** responsible for the ensuring of safe workplaces for workers of all ages. As a project manager organizes age-based planning and redesign of work places. Mediates between involved roles described above and tracks projects and progress. Typical role not available in industry. According to a Boston Consulting Group study, demography management is one of the high critical HR topics, as it is of very high relevance for future work, but companies generally provide a low level of skill level to deal with the problems (Klaffke, 2009, p. 17). Therefore, the role of an occupational age manager providing a cross functional skill set, project management experience and social competencies will become a central role in future work design and employment.

Further, as important external consultant’s researchers, representatives of social insurance companies, mediators, etc. can be involved.

7.2 STEP 2 - INVESTIGATION AND EVALUATION OF THE APPLICATION CONTEXT

The second phase deals with an evaluation and analysis of the current situation. Therefore, the existing data must be assessed and blind spots in available data and knowledge have to be identified. The existing gaps have to be closed in the evaluation phase by conducting further, measurements and assessments of the as-is situation. The specific tool developed to assess relevant data in the industrial context is described in this section.

7.2.1 Evaluation of existing data

The holistic approach suggested for age-differentiated assessment of workplaces builds on the three important factors of an age-centred assessment (1), worker-centred assessment (2) and ergonomy-centred perspective (3). Only the combination of these three points of view enables a holistic evaluation of workplaces in accordance to age-related worker needs. The main goal of this phase is to evaluate existing data with the goal of deriving an overview of which data needs to be further collected and what need for action can be derived from available data. At this stage, several general considerations can already be provided. Further, a tool that enables the combined evaluation of workplaces including all three factors, to complement missing data in terms of standard and age-differentiated ergonomic workplace assessment is introduced in this section.

7.2.1.1 Age-centered evaluation

When focusing on demographic issues, further criteria to prioritize the need for action can be derived from workforce data and worker's perception of work stress. Therefore, the company internal statics can serve to identify the need for action considering three areas. Firstly, from the age structure analysis it is possible to identify departments with a high, or strongly increasing, average age. A high average age might indicate areas where a need for action exists considering replacement strategies and age-related planning. Further, based on the age structure, departments with a high average age also indicate areas where physical improvement measures and age-related workplace design might be needed, thus an age-based prioritization of different departments can be conducted. This prioritization can be supported with sick leave statistics, that include information about department-related numbers and reasons for sickness absence and indicate areas with high risk in terms of different stress factors. Moreover, available statistics of amount and frequency of worker limitations in relation to workplace requirements can assist age-based personal deployment planning or workplace redesign, as well as the introduction of intervention measures.

7.2.1.2 Worker-centered evaluation

The worker-centred approach of considering abilities and limitation can best be supported with evaluations of workers' perceptions for which several validated tools are already available. Therefore, several validated tools are available. Tools that are often used to assess worker perceptions of work conditions and therefrom deriving problems are the, the work ability index (WAI) for general conditions, the FEBA questionnaire (Slesina, 1987) for the subjective perception of working tasks, the Nordic questionnaire (Kuorinka *et al.*, 1987) for musculoskeletal problems, the Borg CR 10 or RPE scales (Borg, 1998) for pain and perceived exertion at different activities, which are often used in combination with body maps (Corlett and Bishop, 1976), to locate the pain or stress sensation. By comparing the perception of work conditions or the experienced strain for specific work tasks, age induces changes can be identified by comparing different groups of workers. Thus, a perception ranking, or a perception need for action of work stress can be generated, based on such data. Such perception data can be generated by means of worker surveys (for an exemplary survey form see Apendix 3), or can be extracted from available company statistics (e.g. exit-interviews) as shown in the previous section.

7.2.1.3 Ergonomics-centered evaluation

First, the detailed evaluation of the results of conducted workplace risk assessment and ergonomic evaluations can reveal existing problems in terms of work place design. Workplaces can be prioritized according to the need for action and ranked according to high risk values. Thus, a risk based prioritization can be derived from the available workplace evaluation. Further, this analysis of existing results can reveal missing data in terms of work place or stress factor assessment in comparison to the worker centred approach. Finally, the comparison of these results of different types of evaluations, as for example perception aspects of work, and statistics of exit interviews, enable a differentiation in types of stress and can thus indicate what types of improvement (e.g. mainly physical, psychological and mental) might be needed, for specific groups of workers. A subjective evaluation of the predominance of work stress can also supported by the NASA task load index (Hart and Staveland, 1988).

Based on industrial requirements, results of the conducted worker survey as well as tools and methodologies to assess ergonomics at workplaces, a tailored methodology and tool has been developed to derive an age-differentiated ergonomic assessment of work places including the age-centred, worker-centred and ergonomic centred perspective. This tool is introduced in the subsequent section.

7.2.2 Methodology for the age-differentiated assessment of workplaces

Based on average changes of human abilities during ageing (see section 2.3.1) and on the multitude of different ergonomic risk assessment methods (see section 2.4.3) it is evident that, based on the increasing strain in elderly workers, such methods should be including the worker- and age-relevant factors. However, as elaborated by the author of this thesis, only a few methods exist, that take individual differences and general age-related changes of abilities into account. (Wolf and Ramsauer, 2019) An in-depth analysis of available ergonomic assessment methods to evaluate physical work stress revealed 46 free of charge methods that are mainly used to evaluate body postures, followed by manual load and repetitive manual material handling activities and action forces. However, for the assessment of working energy turnover and for the combined assessment of different types of stress only a few industry-specific methods exist. In terms of the level of detail of assessment more than half of the methods considered in the analysis evaluate work on screening level, whereas roughly half of these are considered as expert screenings. Further, there is a vast majority of different checklists for workplace assessment, where only those considering age-related assessments where included. With respect to stress determining factors, most methods include an assessment of body postures and duration of tasks, as well as of force exertion, frequency and intensity, awkward postures and the conditions of execution. However, in terms of an age-differentiated assessment, individual human factors are important factors to be considered. In terms of such factors the analysis revealed that gender-related influences are considered in several procedures, while other individual factors as perception of work, individual abilities and age-related assessments are only conducted in a few methods considering specific factors. It can be summarized that even though there exist many work evaluation tools for the different physical work stresses there are only a few tools including the factor age in their grading model. The evaluation of the basic literature and the in-depth analysis of ergonomic assessment methods considering the inclusion of age-related changes made clear that no standards exist, that provide concrete information on age-appropriate ergonomic design. Furthermore, the influences of the factor age have only been taken into account in very few ergonomic evaluation procedures either very rudimentary, for the evaluation of the age-dependent maximum force limits by including different correction factors (cf. REFA 1987, Burandt, 1978 Schultetus, 1987, Jäger *et al.*, 1999; Schaub *et al.*, 2015a), or very unspecific by applying statically data for the intended user population (cf. ISO 11228 and EN 1005). In Figure 55 different ergonomic assessment procedures are summarized and evaluated, considering the industry-important factors derived in chapter 5.

● Criteria considered ◐ Criteria partly considered ○ Criteria not considered

Nr.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Assessment method	BMASK LHT (AUT)	DGUV-240-460 Checklist	FEBA - Questionnaire	OCRACL Checklist	BORG RPE /Cr10 Scale	AUVACL Checklist (AUT)	KIM Lifting, holding, carrying 2001	KIM Pushing, pulling 2002	KIM manual activities 2012	MLT multiple load tool 2010	eLMM Advanced KIM 2012	MonKras Force atlas Screening	NIOSH assessment	OWAS assessment	JSI/SI SI 1995, RSI 2016	BAB / BDS assessment	TLV HAL Limit values	QEC Quick exposure check	ManTRA assessment	HARM assessment	ART assessment	FIOH Assessment	RULA Worksheet	REBA Worksheet	HAL Screening	OCRA Checklist and screening	EN 1005-2,3,4 Assessment	A-Flex Age-different. assessment	REFA Assessment	CHECK-AGE Screening	AWS light Screening	AAWS+ Automotive assembly WS	EAWS European assembly WS	NPW New production Worksheet	IAD BKB Screening	ABA Tech Screening	ERGO-FWS Screening	ATS Age different. tasks Screening	Siemens methodologies
Individual - aspects	○	○	●	○	●	◐	◐	◐	○	○	○	◐	○	○	○	○	○	◐	○	○	○	○	○	○	○	○	◐	●	◐	●	○	○	○	○	○	○	●	●	○
Age	○	○	○	○	○	◐	○	○	○	○	○	◐	○	○	○	◐	○	○	○	○	○	○	○	○	○	○	◐	●	◐	◐	○	○	○	○	○	○	○	●	◐
Computer supported	○	○	○	○	○	○	○	○	○	◐	◐	○	●	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	●	○	●	○
Necessary effort	○	○	○	○	○	○	○	○	○	○	◐	◐	●	○	○	●	○	○	○	○	○	○	○	○	○	◐	◐	◐	○	○	◐	◐	◐	○	○	◐	●	◐	○
Combined assess-ment	○	○	○	○	○	○	○	○	○	◐	●	○	◐	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	◐	◐	◐	◐	◐	◐	○	◐	○	○

Figure 55: Assessment of consideration of different individual factors in ergonomic assessment methods

Methods that consider age for a specific type of stress include the Force-Atlas Screening Method (Schaub et al. 2015), or the ATS method (Keil 2011). The force atlas screening is designed to assess thrust forces in different body postures in the automotive industry. To consider age, the authors suggest correction factors considering two different age groups, namely the young (26-45 years) and the older group (46-60) of workers. It is recommended that age effects can be considered for planning in the older group, but it is also stated that the age effects are of secondary relevance considering the assessment of action forces (Wakula *et al.*, 2009, pp. 187–188). The "Age-differentiated task analysis and screening method (ATS)" builds on a six-step approach to identify age-critical activities during production planning for visual tasks in the automotive industry. The aim of the approach is the collection and subsequent reduction of age-related visual stress. For this purpose, the work requirements imposed by an assembly process are compared with empirical age profiles of production-relevant visual abilities, and the age-criticality of the examined assembly process is evaluated. Based on this evaluation, age limits for a workplace or, workplace improvement suggestions considering different design parameters can be derived. (Keil, 2011, p. 143).

The procedures for the reduction of maximum limit values considering different physical tasks in industry can be beneficial for designing work tasks based on age-related changes. However, for industrial application screening methods that provide a reliable overview of focal points for job improvement are of particular relevance to industry. They are preferred by practitioners, as they can be applied with reasonable effort. (Richter, 2010, pp. 317–319; Egbers, 2013, p. 38)

A screening method for the age-differentiated assessment of workplaces in the steel and iron industry was introduced by Szymanski *et al*. The so called "A-Flex" method composes of three pillars including an age structure analysis (1), a skill analysis (2) and the age-differentiated risk assessment (3). For risk assessment a checklist rating was developed to assess stress deriving from body postures and body movements, and environment conditions. The stress is evaluated in a three zone model based on the execution time and based on limit values derived from international standards and legal regulations in Germany. Besides of physical factors also psychological and mental factors are covered in the assessment. (Szymanski and Lange, 2013) A similar approach for age-differentiated assessment, the so called “Check-Age” method, was suggested by Börner et al.. The Check-Age is based on a screening method developed for the assembly industry. The authors added an age-differentiated assessment by increasing the risk levels for physical assessments (load handling and execution conditions) by one rank category if elderly workers are considered. Further, several yes/no questions for age-specific factors, such as the necessity of maximum forces, or the necessity of high movement speed were added. In addition, risk ratings for seeing, hearing, sensing and information processing were added where the age-specific rating also increases the risk level by one category. (Börner *et al.*, 2017) Lastly the “BAB/BDS” method, which claims to be a holistic workplace assessment, also includes an age-differentiated assessment. Physical stress, environmental conditions, work organization and work safety aspects a graded on a 7-point scale. In addition to the general risk derived in a three zone rating model, there is also a demographic evaluation, where the risk is increased by specific multiplicative factors depending on the basis risk. (Gebhardt *et al.*, 2003)

For all methods listed here, the increase in risk is barley linked to age-related changes of abilities. The methods available on a screening level increase the risk, without a scientifically founded relation, mostly by one category. Thus, a more scientifically grounded relation in assessment of age-differentiated risk is desirable.

An approach aimed at deriving ability based risk levels for rehabilitation purposes was introduced by Sinn-Behrendt *et al.*. The method called “ERGO-FWS” is aimed at deriving individual risks based on the ability level remaining, assessed by occupational doctors. Here, the workplace requirements are analysed using the AAWS methodology procedure. The performance of an employee is set in relation to the full performance and classified with a corresponding percentage value, so that an ability individual risk value can be derived. (Sinn-Behrendt *et al.*, 2004) This method combines the detailed and scientifically founded process of profile comparison methods with ergonomic risk assessment procedures, however, profile comparison methods compare requirements and abilities very detailed on single ability level. Thus, the usage of these method is limited to the assessment of such age-differentiated force and movement sequences where detailed personal ability data is available (Keil, 2011, p. 37). Table 19 summarizes available work place evaluation methods that consider age-related and individual factors in the assessment.

In conclusion, there are some ergonomic methods that already consider the factor age in different ways. Nevertheless, most methods do not consider age-related changes in an appropriate way. Either a differentiation is made on a very general level for limit values (REFA, “Der Dortmunder”, international standards, etc.), or as unspecific increase in risk between young and old groups, as seen in the screening approaches (A-Flex, Check-Age, BAB/BDS, etc.). Only profile comparison assessments take into account individual ability differences. These tools usually do not calculate ergonomic risks, but search a match between worker and workplace, which results in high resources requirements in assessing several worker abilities. The ERGO-FWS tool was introduced to enable ability based risk assessment, but in alignment with the profile comparison methods, it suffers from high resource requirements. Thus, these tools are useful for searching an individual fit between a person with a diagnosed limitation and several workplaces, but are not designed for large-scale use in industry. This clearly shows that, for industrial practice, an approach that allows to derive general recommendations based on the consideration of the dependency of people’s average skill level over a working carer in ergonomic risk assessment is needed (Wolf and Ramsauer, 2019). There is a need for action in workplace assessment methods considering the ageing workforce. An assessment method including the three main age-dependent factors load handling, body postures and energy expenditure is needed. Further, a focus should be put on worker perception of the tasks as the most reliable parameter to identify an age-critical workplace.

Table 19: Age-differentiated work evaluation methods and age critical factors included

Method	Age factors covered	Method of consideration	Source
REFA method	Load handling	Factor for reducing the maximum isometric force when calculating load limits dependent on age groups	REFA, 1987
Biomechanical model "Der Dortmunder"	Load handling	Age-differentiated limit values for load handling based on biomechanics calculations of the compression force in the lower spine	Jäger, 1987 Jäger *et al.*, 2000
International standards	Load handling	Correction factor dependent on age groups for the calculation of reference weight to determine the risk level.	ISO 11228, EN 1005
Force atlas screening	Action forces in different body postures	Measured correction factor for thrust force risk calculation in different body postures for group 45+ compared to group 25-45	Schaub *et al.*, 2011
A-Flex	Load handling, body postures and movement, sensory tasks, environmental conditions	Assessment based on three categories (high, middle, low) for several factors relevant in the iron and steel industry, based on verbally defined anchors and the time of execution. Load handling is assessed without consideration of age.	Szymanski and Lange, 2013
Check-age	Load handling, body postures and movement, sensory tasks, information	Generally increasing risk level by one category. Yes/no questions where yes answers lead to a need for detailed assessment.	Börner *et al.*, 2017
BAB/BDS	Metabolic rate, body postures + movements, Load handling, repetitive actions, environment	Risk level calculation based on KIM and upscaling of the result with an age-factor based on the rating. Age-differentiated rating for postures + movements, load handling, dynamic work, repetitive manual work, some work environment factors, sensory skills and dexterity.	Gebhardt *et al.*, 2003
ERGO FWS	Load handling, body postures, action forces	Comparison of current ability level with stress level not specifically for age but ability based risk assessment. High effort for evaluation individual abilities necessary	Sinn-Behrendt *et al.*, 2004
ABA	Load handling, body postures, information processing	Comparison of requirements and abilities for 19 criteria relevant for car manufacturing and production including load handling, body postures, information processing, workplace safety. Not specifically designed for age but ability based fitting of worker and workplace. High effort for evaluation individual abilities necessary.	Prasch, 2010
IMBA	Load handling, body postures and movements, environmental conditions, sensory skills, OSH		BMA 2000, Schian *et al.*, 2004
ATS	Sensory tasks	Age based assessment of sensory tasks considering age based limit values and derivation of design guidelines	Keil, 2011
KIM pushing and pulling	Load handling pushing and pulling	Risk for assessment of females is calculated as a multiple of male risk (factor 1,3), reasoning that females are considered to possess 2/3 of the strength of males	Steinberg, 2012b

Similar to the approach developed by Keil, and based on industrial needs derived in section 5.4, the approach developed here focuses on a condition-based analysis of work places (Oesterreich and Volpert, 1998). The object of the assessment instruments is thus a worker independent analysis of working conditions within the work system under consideration. Further, the instrument is aimed at creating awareness for age-related ability changes, and therefrom deriving risks. During analysis, the procedure pursues the claim of an occupational science screening procedure. The aim is to identify fields of action for an age-differentiated optimisation of work activities and work system design.

According to the stress strain model, it is necessary to differentiate between stress and strain when measuring and recording the workload. In developing the method, the separation into the above-mentioned levels is taken into account. In a first step, the predominant stress and work demands are recorded (demand determination) based on the relevant age-dependent performance factors. This is done by means of a worker survey in combination with an observation interview. According to the stress strain concept the individual ability determines the individual risk of miss loading. Therefore, in a second step, the standardized and age-dependent skill factors are determined for a reference age (ability determination) and included in the risk calculation. The relevant abilities and the standardized reference age values are derived from literature. The inclusion in risk assessment methods is conducted, based on the examples of the key indicator method for pushing and pulling and the ERGO-FWS method.

This allows a scientifically based estimation of the possible resulting strain on the operator. Further, based on the ERGO-FWS approach an ability based risk assessment for standardized age profiles can be conducted to increase awareness for age-related workplace risks. The schematic structure of the procedure is shown in Figure 56.

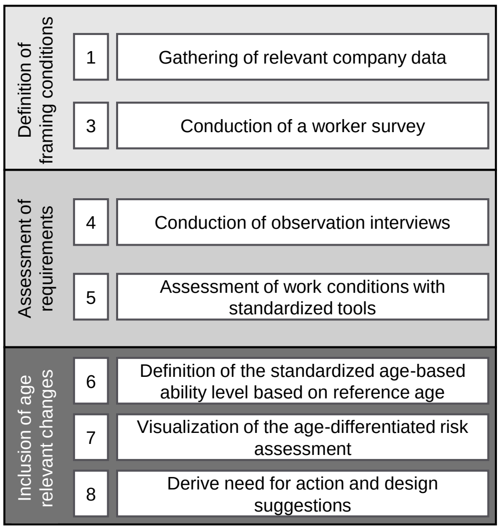


Figure 56: Structure of the analysis procedure

For an age-differentiated evaluation of ergonomic risks at a constant work stress a mathematically formulation of the ability decline with age is necessary, as the risk assessment on screening level focuses on numeric values. Therefore, the data gathered in section 2.3.2.4 was averaged and transferred to a mathematical equation for the three relevant areas of muscular strength and power, aerobic capacity and flexibility of joints. This step was necessary due to the fact that no general ability data, at the aggregation level needed for a screening of ergonomic risk is available in literature. Also profile comparison methods, or detailed FCE assessments and scientific studies as conducted by Rademacher *et al.* and Wittemann provide results of an ability decline over-age or absolute mathematical values for abilities (Rademacher *et al.*, 2013; Wittemann, 2017). For applying the different declines of abilities in age-differentiated risk assessment mathematical functions for these changes in mean values by age were derived and are given in section 2.3.3.

7.2.2.1 Working energy turnover and relative aerobic strain

For the ergonomic assessment of energy turnover, tabulated values according to Spitzer and Hettinger are used to calculate the spending for working postures and movements. Further, the “transport equations” are used to calculate the expenditure of pushing and pulling tasks (Spitzer and Hettinger, 1964, pp. 67–68). For lifting of goods the equations according to Genaidy and Asfour, 1987 are used and holding and carrying activities are modelled with equations derived by Garg *et al.*, 1978. The mathematical calculation of the working energy turnover was implemented according to the industrial need considering the issues in applying the estimation based tool for the classification of heavy duty work places. The working energy turnover was implemented as an assessment criterion to derive statements about to overall physical performance, stress and strain levels at workplaces. The evaluation of energy expenditure is conducted by limit values in accordance to the BAB procedure (Gebhardt *et al.*, 2017, p. 24; Bokranz and Landau, 2012, p. 261; Szymanski, 2006, p. 24). For the age-differentiated assessment of the energy turnover a declining aerobic capacity and maximum heart rate was chosen as the limiting factor (Zülch, 2010, p. 86) and the evaluation is based on the relative expenditure level in comparison to the estimated age-based maximum values (Ilmarinen, 1992b; Kenny *et al.*, 2016).

Table 20: Quantification of relevant age-related changes for physical capacity

Endurance					
Domain	Area	Effect	Age-related decline	Source	Type
Endurance	Aerobic capacity	Decrease in Vo2_max, HR, aerobic capacity	5-15% loss per decade after 30 years (1% p.a.)	Hawkins and Wiswell, 2003 Bellew *et al.*, 2005	Linear until 40 and 70 years with different slopes (Babcock *et al.*, 1992; Fleg *et al.*, 2005)
			1% decline per year after age of 20	DeZwart *et al.*, 1995	
			10% loss per decade (1% p.a.)	Shephard, 2000	
			Total loss of 30% between 25-65 years	Ilmarinen, 2002a	
			Total decline of about 20% between 40 and 60 years (1% p.a.)	Kowalski-Trakofler *et al.*, 2005a	
			Total decline of 60% between 40 and 70 years (1,5 p.a.)	Chan *et al.*, 2000	
Average			0.94% p.a. until age of 40 years, 1.37% p.a. afterwards		

For calculation of the decline in the domain of aerobic capacity, values gathered from literature for decreasing aerobic capacity, maximum heart rate, or maximum oxygen intake were averaged (see Table 20 and Table 5) and transferred in a mathematical formula, which expresses a start in decline after the age of 20 years. Based on the remaining maximum capacity and the working energy expenditure on a workplace per workday, the relative aerobic strain can be calculated. The relative aerobic strain can be evaluated according to individual limits, thereby deriving an age-based risk value. Further, instead of using the general value it is also possible to manually apply a specified value for the actual remaining aerobic capacity or the individual maximum oxygen intake, which could be determined for by a company doctor. Therefor an individual risk value can be derived depending on either workers age or their remaining physical capacity.

Figure 57 shows an exemplary assessment of the energy turnover at an workplace with a consumption of 2001 kcal per workday. According to values from literature an average 25-year-old person works at 30% relative aerobic strain (RAS), thus below the 8-hour long term limit of 33% RAS. However, according to the calculation an average 65-year-old person is already working at an RAS of 49%, thus almost at the level of suggested short term maximum RAS. The colour in the figure is indicating the individual risk level according to the RAS value on the secondary y-axis.

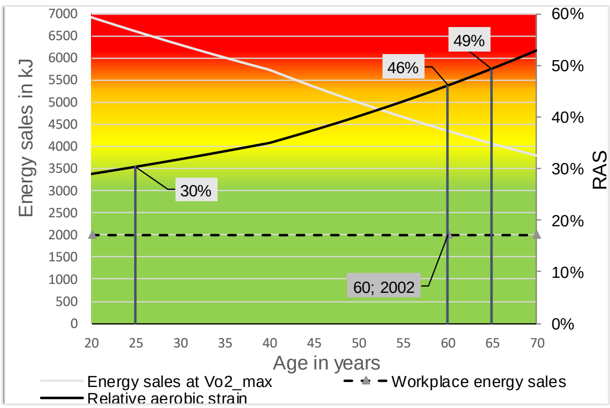


Figure 57: Age-differentiated evaluation of energy turnover according to aerobic strain

7.2.2.2 Load handling

For the ergonomic assessment of manual material handling the standard key indicator methods (KIM) were chosen to accomplish the requirement of building on available results from the case companies. Further, the key indicator methods are one of the most used assessment methods in related industries.

As the KIM are designed to assess a single type of work tasks and the assessment procedure has known problems in evaluating workplaces with varying loads, the multiple load tool was implemented for a combined assessment of different types of manual material handling. For the age-differentiated assessment of manual material handling declines in muscular force and power were chosen as the limiting factor, as maximal muscle strength is of major importance for the carrying of goods (Nygard *et al.*, 1988, p. 18; Snook, 1987), isokinetic and concentric strength are major determinants for lifting performance (Kenny *et al.*, 2008, p. 615), and muscular strength and power are important prerequisites for maintaining occupational performance and work ability (Kenny *et al.*, 2016, p. 8). The relevant values are summarized in Table 21. For the calculation of the decline of force the values gathered for muscular strength and muscular power were transferred in a mathematical formula using mean values for 5-year age groups starting the decline at the age of 30 years (see). The factor calculated by this formula is the on average remaining force at a certain age. The decrease in muscular power, as modelled, also corresponds to study results measuring the isokinetic lifting force for back muscles, resulting in reductions around 40% between the ages of 25 and 60 years (Hamberg van-Reenen *et al.*, 2009, p. 1119).

Table 21: Quantification of relevant age-related changes for load handling tasks

Muscular power and strength				
Domain	Area	Effect	Age-related decline	Source
Force	Muscular strength	Isometric maximum strength (holding, carrying)	Peaks between 25-30, 95% at age 40, 85% at age 50, 75% by age 65	Aoyagi and Shephard 1992, DeZwart *et al.*, 1995; Gall and Parkhouse, 2004; Vitasalo *et al.*, 1985, Ilmarinen 2001,
			Peaks at 20 then decrease by 10% per decade till 60 (1% p.a.)	Mazzeo 2000 cited from Boenzi *et al.*, 2015
			Decreases by 12-15% per decade after age 50 (1.35% p.a.)	Kamel, 2003; Doherty, 2001
			0.8-5% per year depending on muscle group	Aoyagi and Shephard, 1992; Savinainen et al., 2004b
			Peaks between 20-30 then decreases with 1.5% p.a. till age of 55 years. Afterwards decreases with 3% p.a.	Hollmann and Strüder, 2009; Scherf, 2014 Börner *et al.*, 2017
			Total decline of up to 45%	Shephard, 1999; Bellew *et al.*, 2005
		Concentric muscular strength (lifting)	Comparable to isometric strength with 8-10% per decade (0.9% p.a.)	Lindle *et al.*, 1997
		Isokinetic strength (lifting)	Decreases by about 40% between the age of 30 to 60 (1.33% p.a.)	Hamberg van-Reenen *et al.*, 2009
			decreased with age (r = -0.41, P<0.001)	Latikka *et al.*, 1995
		Muscular Power (dynamic actions with force)	Total decrement in muscle power of 30–45%	Shephard, 1999; Bellew *et al.*, 2005
			10% more than muscular strength between 20-80 years	Kenny et al 2008
Average			Isometric muscular strength 1.25% p.a. till age of 50 and 3% p.a. afterwards; Lifting strength 1.1% p.a.; Muscular power 1.375% p.a.	

The factor of isometric strength is applied as a divisor on the result of the key indicator method for carrying and pushing/pulling to calculate the age-differentiated risk value and the decline in lifting strength is used as a divisor for lifting. Further, instead of using the general value, it is also possible to manually apply a specified value for the actual remaining muscular strength in comparison to an average 30-year-old person, which could be determined for example from a company doctor. This allows the derivation of an individual risk value for material handling depending on either, workers' age or their remaining muscular power. It shows the general decline in muscular strength and the formula used to calculate it in the model.

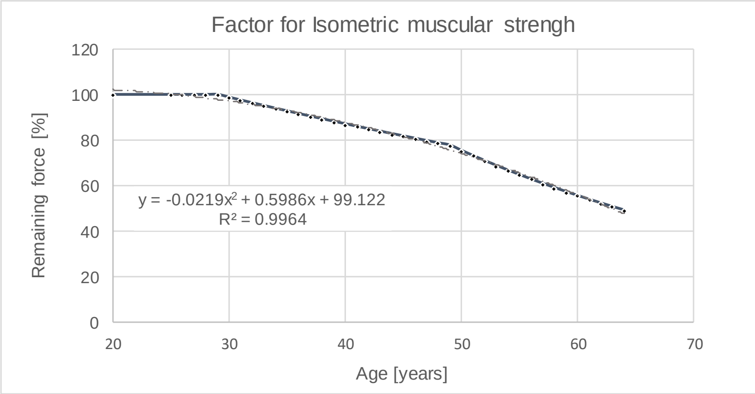


Figure 58: Decline muscular strength with age

Applying the multiplier as mentioned on the result of the KIM increases the risk value by an age-dependent amount. Similar to the ATS method described earlier, this can be used to derive age limits or special limits for workers with impairments of physical abilities. An exemplary result of the application of this age multiplier is shown in Figure 59. For a manual material handling tasks composed of pushing, lifting and carrying activities a resulting age independent risk value of 37 points for male and 42.5 points for females is derived by applying the multiple load tool assessment. Applying the age based reduction in muscular strength to that risk value, a hypothetical increase of the risk over the worker age can be visualized to generate awareness for the increasing strain and risk with increasing age as shown in Figure 59. It can be seen that by applying the calculated age multiplier the risk value increases depending on age to 45 points for a 55-year-old and to 49 for 65-year-old men.

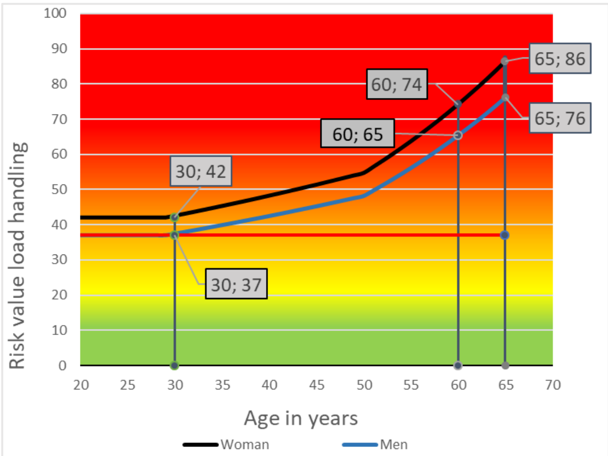


Figure 59: Age-differentiated assessment of load handling

Based on the zone model for risk assessment (see section 2.4.3) a workplace with a risk score of 37 point might be judged as acceptable, considering that there might be workplaces with higher risk values. On the other hand, workplaces with risk values around the 50-point limit call for immediate redesign.

7.2.2.3 Body posture

For the ergonomic assessment of static postural work mathematical point ratings for body postures are available in German assessment methods (e.g. EWAS, BKB, etc.). These assessments refer on empirical values to describe the risk of maintaining static body postures for a prolonged time. These series of numbers were extrapolated in mathematical formulas to calculate point values based on the total time of maintaining a posture per workday, to enable a combined assessment of different body postures. The different risk points per posture are added up to a total score of postural risk. For the age-differentiated assessment of postural loads, a decline in flexibility of joints and tendons influencing the ability to work in awkward postures (Boenzi *et al.*, 2015, p. 606) and of the static endurance time decrease, influencing postural strain from static work (Hamberg van-Reenen *et al.*, 2009, p. 1118; Latikka *et al.*, 1995, 328) was considered as the limiting factor for modelling, as specified in Table 22.

Table 22: Quantification of relevant age-related changes for body postures

<table>
<tr><th colspan="5">Postural work</th></tr>
<tr><th>Domain</th><th>Effect</th><th>Age-related decline</th><th colspan="2">Source</th></tr>
<tr><td rowspan="3">Body postures</td><td>Flexibility of joints and tendons</td><td>20-30% decrease from age 30-70 (0.5% p.a.)</td><td colspan="2">Johns and Wright, 1962
Chapman et al., 1972
Chapman et al. 1992</td></tr>
<tr><td rowspan="2">Static endurance time</td><td>Decreases by about 33% for back muscles between age 30-60 years (1.1% p.a.)</td><td>Hamberg van-Reenen et al., 2009</td><td rowspan="2">Not linear (Hamberg van-Reenen et al., 2009)</td></tr>
<tr><td>Decreasing with age (r = -0.27, p = 0.008)</td><td>Latikka et al., 1995</td></tr>
<tr><td colspan="2">Average static endurance</td><td colspan="3">1.1% p.a.</td></tr>
</table>

A linear annual decline of 1.1% for static endurance of back muscles was chosen to model age-differentiated assessment of postural stress. This modelling also corresponds to the measured decrease of around 33% between the age of 35 and 60 years in back muscle endurance time for static tasks (Hamberg van-Reenen *et al.*, 2009, p. 1118). The factor calculated by this equation is the on average remaining static endurance in the back at a certain age, which is a feasible indicator for postural stress. This factor is applied as a divisor on the result of the EAWS assessment of postural stress, to calculate the age-differentiated risk value. Further, instead of using the general value, it is also possible to manually apply a specified value for the actual remaining static endurance in comparison to an average 30-year-old person, which could be determined by an occupational doctor. Therefore, an individual risk value can be derived for postural loading depending on either, workers age or his remaining muscular power. Further, special activities involving awkward postures (overhead work, kneeling, squatting, twisted body, etc.) can be screened considering age-related limit values and can be judged in relation to declining flexibility of joints and tendons and specific limitations found in older worker populations (see Wittemann, 2017, p. 58; 89).

7.2.2.4 Overall evaluation

In accordance to the EAWS procedure also an overall evaluation of the workplace is provided in the assessment as shown in Figure 60. Therefore, the points for load handling and postural stress are summarized to physical work load category. Further, the overall energy expenditure is provided as overall stress defining evaluation and a risk value for manual material handling can be considered, calculated by the Key Indicator Method (Steinberg, 2012a). For the workplace risk value, the maximum value of the three categories is to be considered. However, all categories should be considered in regard to high values that can be improved for a better ergonomic workplace design.

In the **body posture** area, several industry typical body postures and movements were included. Also stress moderating factors as support, working at or overhead height, and bending of the upper body are included in the assessment. The risk rating of static body postures and body movement is conducted based on the EAWS procedure, with empirical point values based on the time of execution. The risk per posture or movement is calculated by summing the relevant times per posture and day and calculating the according risk point value. The overall risk value for postural risk is determined by summing up the single risk values for that category. The total postural risk is afterwards adapted by the age-based multipliers for postural stress and strain as described in the previous section.

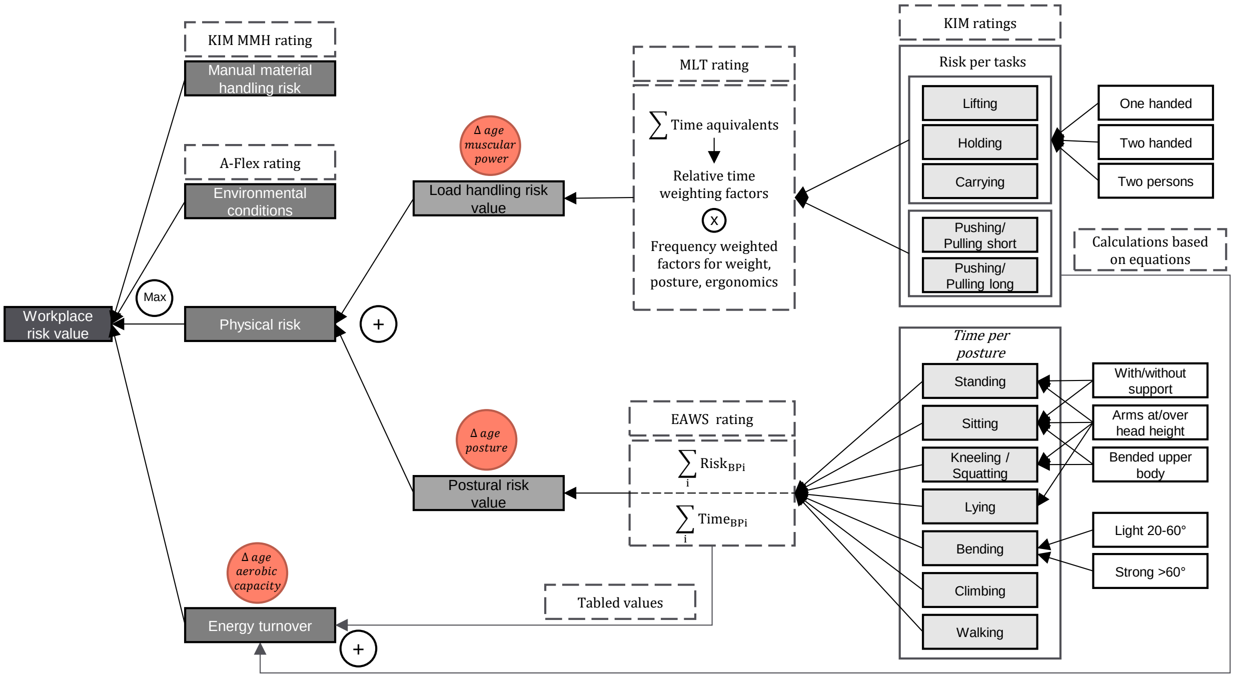


Figure 60: Structure of the overall age-differentiated workplace assessment showing schematically how the work place risk value is derived based on, repetitive, environmental, physical and working energy based work stress and strain factors

For **manual load handling** of loads with a weight of more than 3 kg a load handling risk value is derived. In the category lifting, holding and carrying activities are summarized considering one- and two-handed execution as well as an execution in a team of two persons, as suggested in the Multiple-Load (MLT) procedure (IAD, 2010). The risk deriving from pushing and pulling of goods is calculated in a separate group and, based on the MLT, these activities are further divided in short and long distance execution. The individual risk for the single tasks is calculated based on the key indicator method for lifting, holding and carrying. For a combined assessment of different load handling activities, the different time weightings are translated in time equivalents and summarized. According to the algorithm suggested in the MLT, based on the relative time weightings and frequency averaged values for load, posture, and execution weightings, a total value for the risk of load handling is derived. The total load handling risk is afterwards adapted by the age-based multipliers for muscular force and power decline, as described in the previous section. According to the EAWS procedure both risk values for postural load and load handling stress are combined to a physical risk factor.

The third value considered in the assessment is the **overall energy turnover** at the workplace. According to the Austrian “Schwerarbeiter Verordnung” (heavy worker regulations) it is necessary to define workplaces with high physical workloads based on the energy expenditure as heavy workplaces, where specific regulations apply. To determine the overall energy expenditure per workplace the energy spending from static postural work and dynamic load handling work are combined. For postural work, the time per posture and movement are used for calculating the according workplace energy turnover based on the tabled values for working energy expenditure (Spitzer and Hettinger, 1964), and for the load handling activities formulas for calculation the energy expenditure are used per activity (Genaidy and Asfour, 1987). To calculate the energy turnover task specific values as initial and end position per lift and worker-specific values as the body weight and gender are used. The overall energy turnover is classified in risk levels according to Table 4. The age-specific evaluation is conducted based on the general aerobic capacity decline as explained in the previous section. Figure 61 summarizes the consideration of age-related changes in the three considered categories, also stating the mathematical calculation of the age-dependent factor for the remaining capacity per category.

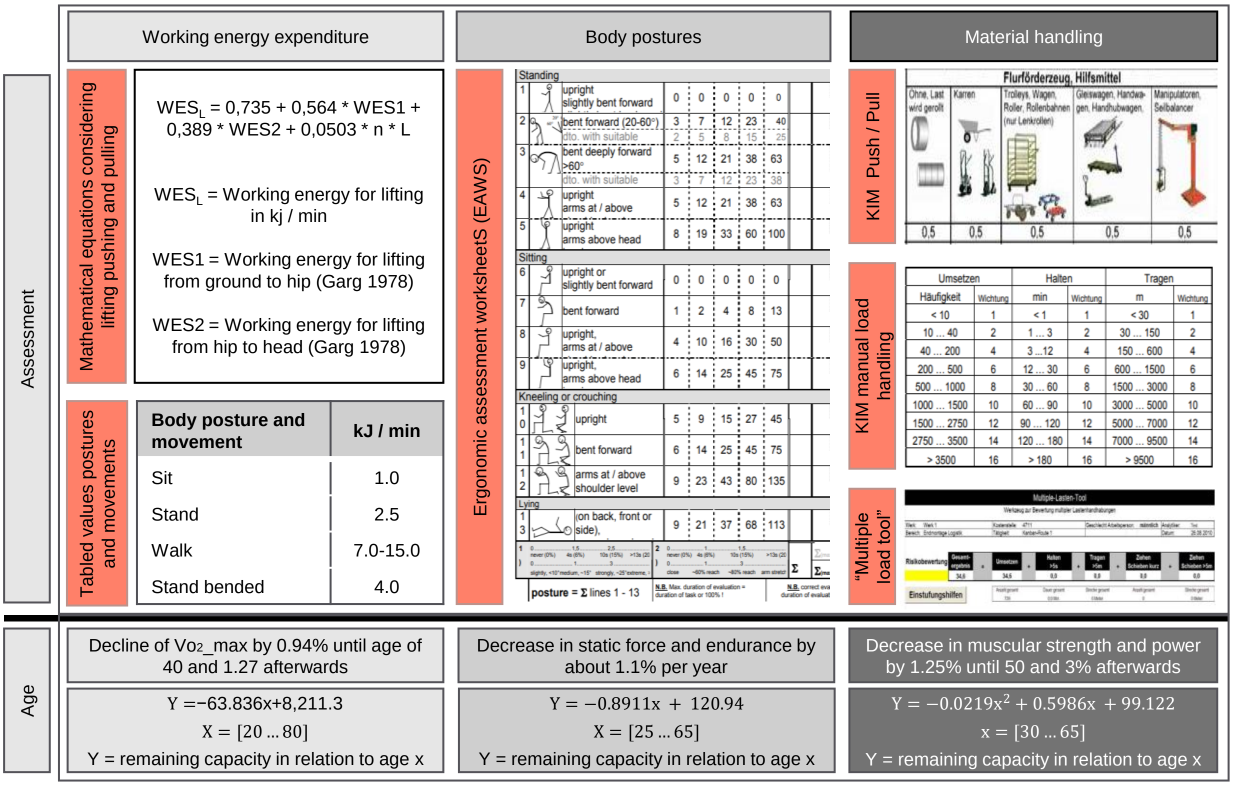


Figure 61: Age-differentiated workplace assessment tool, methods used and consideration of age (pictograms from the original method's worksheets (IAD, 2010; Schaub, 2007; Steinberg, 2012b))

7.2.3 Tool for industrial application

For the evaluation of an age-differentiated risk factor at workplace level the methodology described was implemented in an easy to use excel file. A major requirement considering the assessment of multi-tasks workplaces is the combined assessment of different work tasks. To achieve this the input for the calculation file was designed to be task related and the procedure was designed so that the user enters a combination of different work tasks described by their main domain of stress and the stress-defining parameters. This approach was also beneficial taking into account possible measures for elderly workers as job-rotation or the exclusion of several tasks, as single tasks can be deleted from the assessment without the need for a total reassessment. The input masks for an exemplary evaluation is shown in Figure 62. In five steps, different relevant parameters for the evaluation are required either as numerical values, or as a choice of standard variants in drop-down lists.

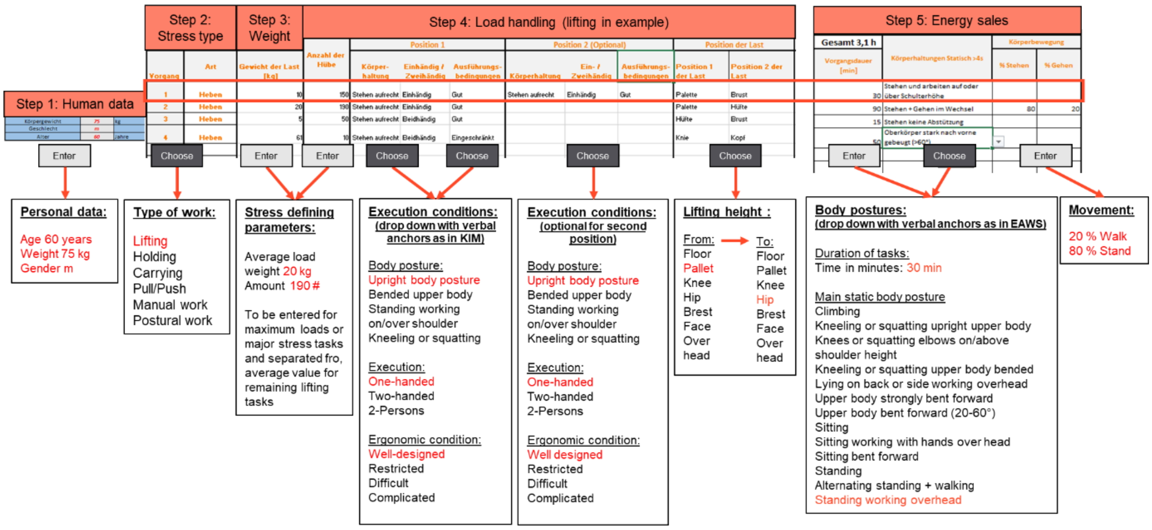


Figure 62: Input mask of the evaluation tool

In step one, workplace name or identifier and personal information about the intended worker population or a specific worker under consideration are required. Input parameters to define are the worker's age or the medium age of the intended user group. Further, the (average) body weight is required for the calculation of the energy turnover at the workplaces. The gender of the intended users can be specified, as there are lower limit values for female workers over all categories. In step two, the main type of activity for the tasks has to be defined out of a drop down list including manual material handling tasks (lifting, holding, carrying, pushing and pulling) and static postural work. In step three, for all types of material handling the load has to be specified. To avoid averaging effects in terms of high loads that are handled rarely, and low weights that are handled very often, high loads should be considered in a separate entry, and average values should only be derived for similar objects. Based on the calculation of the risk value according to the MLT procedure several load handling operations can be defined. In step 4, the other stress defining parameters are to be entered to the sheet. To increase usability, different types of main stress require different input parameters and only relevant parameters are shown to the user. In the example in Figure 62 , a lifting activity is presented and the relevant input parameters such as amount of lifts, body postures during lifting, and ergonomic execution conditions have to be defined for either a stationary workplace, or for two separated positions if the task involves that. Further, for the calculation of the energy turnover for the lifting task, the vertical start and end position of the load has to be specified based on predefined heights from floor to overhead height. The lifting heights are calculated by the procedure according to standardized values from literature. For holding tasks, the holding time in seconds, and the ergonomic conditions (based on KIM) as well as the conditions of execution (one-handed, two-handed, two persons) have be specified. For carrying tasks, the distance covered, the body posture and ergonomic as well as execution conditions are required. Finally, for pushing and pulling tasks, the type of the activity (<5m short, >5m long) has to be identified and besides the ergonomic and execution condition, also the required precision and the type of transport vehicle can be specified according to the KIM PP. For the assessment of repetitive manual work tasks, the standard KIM was implemented in the tool. The input parameters for this section are ident with the parameters needed for the original KIM MMH. Finally, in step 5, the duration of the whole task has to be defined. Further, input parameters for the evaluation of body postures and movements are required and body postures are available from a dropdown list containing 16 different postures as presented in Figure 62. If the work tasks consist of walking and standing activities, it can be selected from the list and the percentage of walking and standing can be specified.

The result of the age-different assessment is presented in a dashboard aiming to enhance the awareness for the need for action considering the ageing workforce. The overall workplace value can be used to prioritize the need for action per workplace. The overall results are displayed as shown in Figure 63. Basic data considering the workplace identifier (Name, number, etc.) and the group of workers under consideration, as well as the assumed ability decline in that group are displayed in the top row. The workplace results are presented in terms of an overall value combining physical stress of body postures and load handling. In addition, the values for overall working energy turnover, including the evaluation of the overall relative aerobic and stress from repetitive manual material handling are evaluated. Per category of work stress (lifting, holding, etc.) the maximum values for the main stress determining factor (weight, time, amount, etc.) are displayed next to the category and averaged values for the category are calculated. Further, the category individual sum-score of the specific risk, and the specific working energy turnover per category is provided.

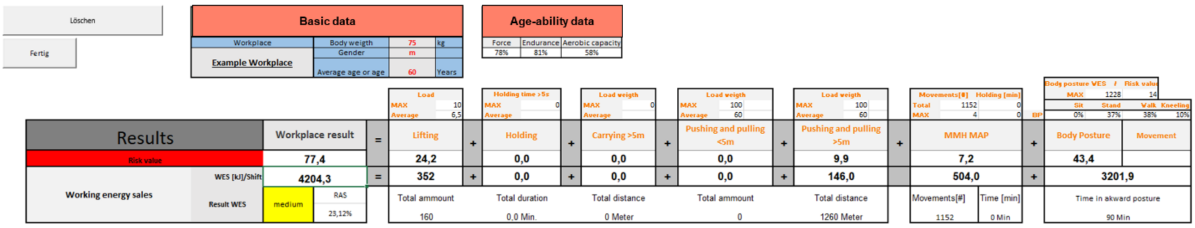


Figure 63: Output of the tool for the overall evaluation of the workplace

A more detailed assessment of the physical work stress is also provided, as illustrated in Figure 64. In the detailed assessment, the area workplace evaluation summarized the important overall scored considering load handling (LHC), body postures (BP), repetitive manual work (RMW), working energy expenditure (WEE) and relative aerobic strain (RAS). For each category, the norm value derived by application of the specific standard method is provided and also the age-differentiated value is displayed next to it for the chosen age for assessment. Individual results are marked in colours according to a four quadrant sector, whereas green indicates low values, where no need for action exist. The yellow category, according to other standard methods, indicates an increased risk level where workers with limited abilities and resistance might face problems. Here, a detailed assessment for such persons is advisable and workplace improvements might be needed for a specific group of workers. The orange category indicates a high stress level, with an increased risk for all workers. Improvement measures should be introduced to lower the work related stress. Finally, the red level indicates a very high risk of overloading for all workers, where a redesign of the work situation is immediately needed to protect workers' health and safety. According to the age based ability decline, the risk within the age-differentiated assessment are always higher as the standard ratings. Also, the RAS is increased for older workers according to the declining maximum aerobic capacity. If the workplace evaluation results in medium or high risk levels, the work process evaluation provided can be used to identify the root causes of the high stress levels.

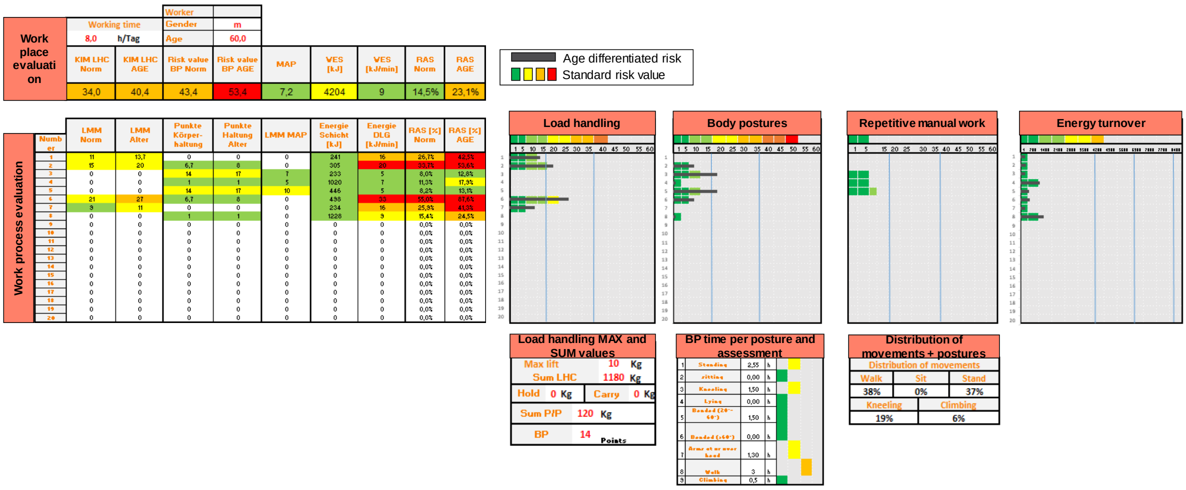


Figure 64: Detailed results of physical work stress

In the work process evaluation, the results for each individually entered work task is shown. This enables the identification of processes that are causing the stress for each category. Further, it enables to identify the relevant levers for workplace improvement, or specific work tasks to eliminate, reduce in duration, or improve in terms of execution conditions. The result charts provided convey a clear overview of the assessment result for the standardized (coloured bars) and age-differentiated (grey bar) evaluation and on top of the tables the aggregated risk score for the age based evaluation of the category is visualized. This enables a clear and traceable interpretation of the results provided. In addition, the distribution of postures and body movements is provided and the total time of relevant awkward postures is indicated. Moreover, some important detailed information per category are summarized next to the charts. For the category of load handling besides the risk value, also the sum of the manipulated weights for lifting and pushing and pulling activities are provided. For the category of postural work, the time sum per assessed posture is provided and the according age-differentiated risk is illustrated in the colour scheme according to the grading system of the A-Flex method. Finally, graphical representations of the increase in risk factors over age are presented as shown in Figure 65, to highlight the age effects and enable future oriented planning.

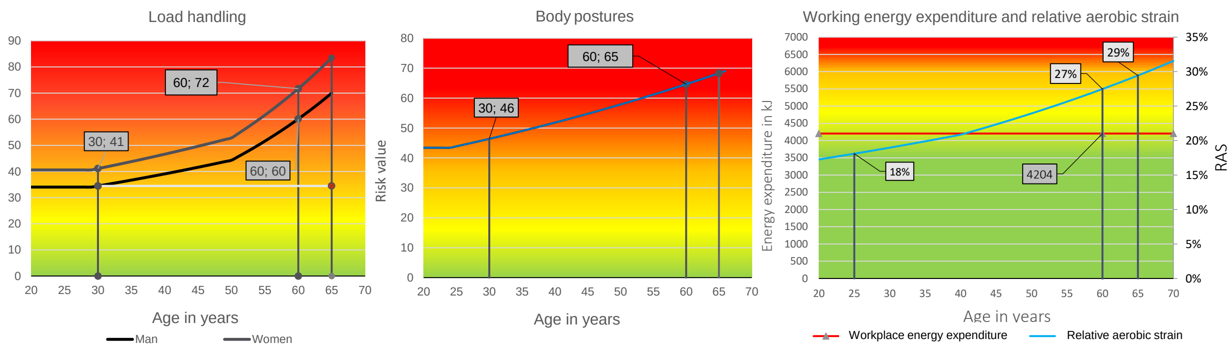


Figure 65: Increase of risk values over age for load handling, body postures and energy turnover

The tool is designed to enable a user friendly and age-differentiated assessment of work stress and provides the results in a clear and comprehensible way to enable solution oriented identification of suitable measures. The main goal to increase awareness for the factor age in HSE is met by the comparing evaluation of younger and older operators and by plotting age based risk increase over normal working age from 20 to 65 years. Therefore, RQ1 ca be considered as answered by evaluation results of the developed tool.

7.3 STEP 3 - DEFINITION AND PRIORITIZATION OF THE NEED FOR ACTION

After the evaluation of workplaces, the generated data has to be analysed and the need for action can be derived based on the results. Projects within this scope can have different purposes and strive for different goals. For example, projects can be conducted to prepare for an ageing workforce proactively by taking into account future changes and prepare plans for how to cope with expected changes. However, his strategic approach is barely conducted in industrial state of the art. Mainly projects are initiated due to emerging problems of workers with current working conditions. Thus, the goal of the second type of project, is in improving work by adapting existing workplaces to the changed needs. Therefore, based on the data suggested in section 7.1.1, a twofold prioritization strategy is introduced.

7.3.1 Need for action for strategic projects

If the focus of the project is future-oriented, a comparison of risk assessment data and the age structure analysis has to be conducted. Within the physical stress domain, the age-based need derived from the department's age structures are to be compared with medium and high risk level workplaces. The task priority is the highest where, on average, old workers meet high work demands. Here, replacement and reallocation or job-rotation and job-sharing strategies should be prioritized. Examples for such procedures can be retrieved from literature for workforce scheduling (Yoon *et al.*, 2016; Egbers, 2013), qualification based scheduling (Hochdörffer *et al.*, 2016) and for an holistic personnel development and qualification-based replacement approach (Szymanski, 2016). On the other hand, the project can aim for improvements of the working conditions, considering an ageing workforce. For this use-case a detailed plan has been developed that is introduced in the following section. For the improvement goal perspective, the ergonomic risk assessment results have to be aligned with worker's experienced strain level and thus the perception of the work tasks and places.

7.3.2 Need for action for improvement projects

For improvement projects, the need for action can be derived from the results of the ergonomic assessment. The prioritization of the need for action follows the general ergonomics approach where the priority of improvements is set according to the workplaces risk value. On a higher level, aggregated workplace values, as derived in the suggested methodology, enable the cross-department comparison of the need for action at workplaces and can thus be beneficial if low resources for ergonomic improvements are available. Thus the prioritization of workplaces should start at departments with a high share of workplaces with a high risk rating (red category), as such take on the highest priority and need urgent implementation of measures. After the treatment of such workplaces, the priority of implementing measures should be conducted according to the risk values derived in the assessment prioritizing the overall highest value in the different departments. As a prioritizing rule for age-based work improvement the age-differentiated assessment methodology increases the priority in case of a mismatch in terms of high physical work requirements and diminishing physical capacity by increasing the according risk value. Thus, the increased need for work stress reduction in face of on average less resilient workers is included by the age-differentiated assessment.

7.3.3 Classification of fields for action

After identifying the need for action, the identification of related fields for actions is needed. In connection with the needed assistance and reduction of work related stress and strain, there is a need to develop a sensible system for the classification and categorization of various available solutions, taking into account a change in the general prerequisites in older age. Such a classification should address load reduction parameters on a superordinate level and at the same time provide a categorization of measures according to their level of impact. In view of concrete work situations and real problems, both should serve to facilitate the targeted selection of specific solution concepts considering the company and application context. The framework is aimed to enable the transfer of general methods and technological possibilities described in sections 2.4.4.1, 2.4.4.2, and 2.4.4.3 to specific requirements in companies in connection with the loading situation at selected workplaces, derived from the ergonomic assessment.

To define possible reactions on age-related work stress, a theory of assistance is needed and such a theory is currently not available. Therefore, RQ2 directs towards the question how to select suitable solutions considering workplace design for an ageing workforce. The applicable basic model of the stress strain concept was introduced in section 2.2.6. Specifically, for the evaluation or selection of suitable solutions in workplace design this model has to quantified, which can be done according to the psychophysical scaling models introduced by (Borg, 1978). Originally based in sports science, Borg focused on the effectiveness of training and the influence of different abilities on perceived effort in relation to physical performance. Mathematical functions were derived based on measurements of physical activity in relation to the tasks and perceived effort. Test on different tasks all resulted in a power law with different constants and exponents. For example, based on experimental testing of perceived effort in relation to physical performance on an ergometer (physical work that includes big muscle groups i.e. heavy physical work) the mathematical relation was expressed as:

$$R = a + c * (P - b)^n$$

where *R* is the intensity of the response expressed as subjective impression (RPE-scaling), or objective reaction in terms of e.g. the heart rate, *P* is the physical intensity of the task expressed in Watt, *a* is a perceptual constant, *b* is a physical constant, c is a measured constant and *n* is the exponent that is related to the task performed. Different experiments resulted in values of *n*=1.6 for bicycle ergometers (Borg, 1962; Borg, Edgren, and Marklund, 1970), *n*=1.45 for weight lifting (Stevens and Galanter, 1957), and *n*=1.6-1.7 for force of handgrip while squeezing a dynamometer or for foot pressure (Stevens and Mach, 1959; Eisler, 1962). Many other experiments on other muscular activities have shown an exponent of about the same size (see review by Stevens, 1972 cited from (Borg, 1978, p. 339). However, the functions derived from the experiments are always positive accelerated (n>1) power functions as illustrated in Figure 66.

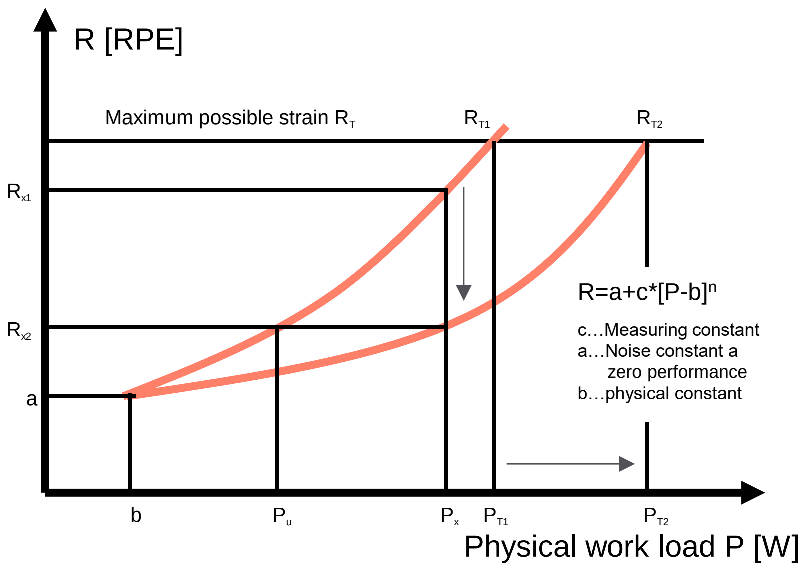


Figure 66: Variation of perceived exertion (Borg, 1978, p. 343)

The constant a is defined as the value at which an increase in performance does not result in a change of perceived exertion (value at rest) and usually accounts for a small percentage of the maximum exertion. The variable b is usually zero. (Borg, 1998, p. 27) Based on this mathematically model the individual exertion as a response to the physical performance can be calculated knowing the personal limits. Further, when aiming for a specific level of perceived exertion, the formula can be used to determine the required physical load, i.e. their determining factors (Borg, 1998, pp. 27–28), The two curves represent two individual functions of the same tasks. One of the subjects (labelled 2 in the figure) is assumed to be fitter (e.g. stronger) and can therefore lift a heavier weight, or has a better physical performance P. Therefore, also a higher maximum performance (P_{T2}) can be reached by this subject. Based on the main foundation of the model, that all individuals will experience work at the personal performance limit (P_T) equally exerting ($R_{T1}=R_{T2}$) a comparison of two individuals at various submaximal intensity levels, as well as calculations of relative response rates and relative stimulus values is possible. It is also shown how training reduces the perceived exertion for a certain submaximal level (P_x), until the weaker individual can manage the same maximum performance as the other individual (arrows in the figure). Also a prediction of how much the subjective effort will go down with training for a given submaximal work load is possible if the mathematical equation is known. (Borg, 1978, pp. 342–343)

Based on this model, a theory of ergonomic intervention for healthy workers in relation to age-based ability-decline can be derived. While workplaces with high energy turnover should be tackled in terms of stress reduction, workplaces with lower energy ratings and high ratings in load handling or body posture evaluations should also be considered in terms of strain reduction. General measures from primary prevention area are always aiming at reducing the work stress. A reduction in working time, (partial) automation of work tasks, or tasks division between human and robot, all reduce the physical stress experienced by the worker, if not replaced by more exerting tasks. Thus, such measures can be seen as beneficial for all workers considering high stress workplaces. Considering an ageing workforce, it was shown in literature that especially strain is an adequate indicator for designing age-appropriate workplaces. Given an existing work stress, or performance requirements, it is shown in the figure, that physically less capable individuals will act at higher RPE levels. Therefore, measures from secondary prevention, that can modify perceived strain, are especially suitable for the improvement of work places in relation to an ageing workforce. Thus, besides already mentioned training of physical abilities, all kinds of ability modifying interventions can be judged as especially beneficial for designing physically age-appropriate workplaces. In terms of technical assistance particularly, passive exoskeletons can be seen as such systems, as the objective stress from the tasks remains the same but the perceived strain is changed due to load redistribution in the body (see Figure 67).

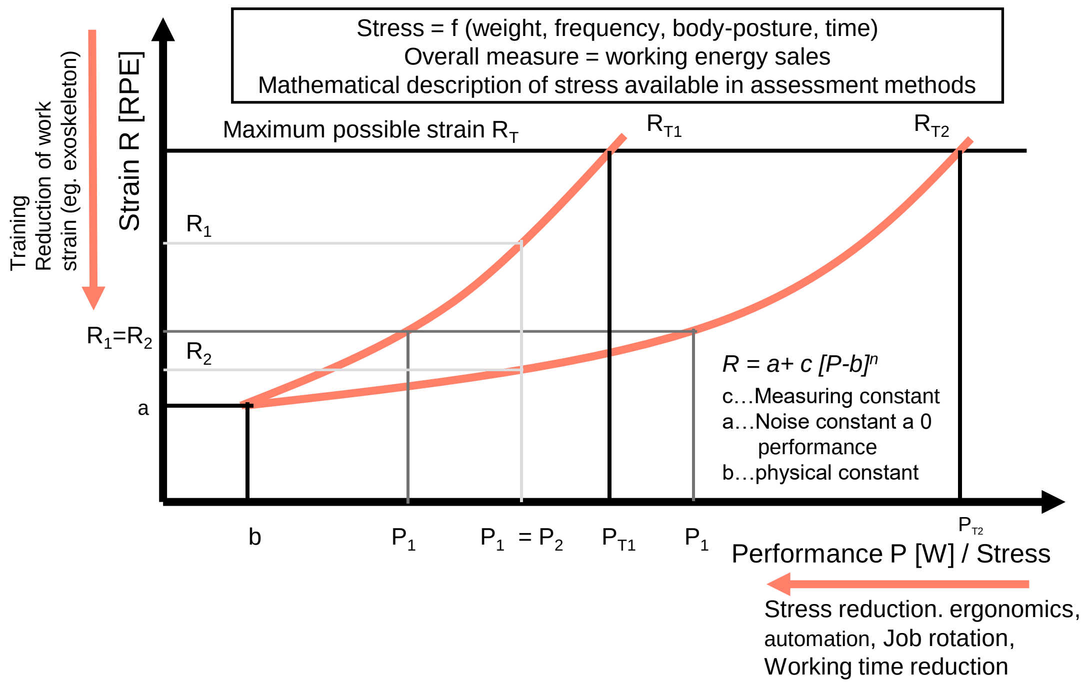


Figure 67: Theory of ergonomic intervention outcomes

Based on this model, also a prediction of the effects of physical assistance system can be drawn before implementation, if either the rating of perceived exertion, or the mathematical formulation of the stress-strain ratio for the specific work tasks is known in combination with the load, or the strain reduction provided by implementing the measure. For the mathematically formulation of the relations stress can be described as a function of weight, frequency, posture and working time for specific tasks as available in ergonomic assessment methods (see figure Figure 29), or, for overall consideration as the working energy expenditure per workplace and time, which can be expressed as a performance in Watt. Based on Borgs psychophysical scaling functions, in combination with mathematical formulations of an increase in strain with age for a constant workload, as presented by (Börner, 2019), also ergonomic age-differentiated workplace assessment could be conducted without relying on individual ability measurements, or population specific ability forecasts.

Methodologically, the development of the categorisation and classification logic considers an occupational science approach which is based on the stress determining parameters relevant for physical job evaluation (time, frequency, posture, weights, etc.). Depending on the assessment dimension (energy expenditure, postures, physical forces, manual material handling, manual work processes), several influencing factors, are included in the load assessment using different calculation models. However, the assessments have in common that the risk is indicated in the form of a risk index, which results from the multiplication of the two parameters intensity (I) and duration (D) (see Figure 29). The risk index is then compared with empirical limit values and, depending on the result, recommendations for action are made to achieve the necessary changes. However, a recommendation which conditions should be changed in the workplace, is generally not provided by common procedures. Since the individual exposure parameters, are central levers for the improvement of the exposure situation and allow the derivation of corresponding design measures, a methodology that draws on this information and links possible solutions to the exposure parameters would be beneficial. Also different measures gathered in the literature analysis can be beneficial to tackle different stress parameters and reduce specific exposures. While work time related measures decrease the exposure to a work stress, ergonomic modifier redesign of workplaces can tackle load weight, body postures, etc.

With the suggested categorization and classification, it is possible to identify the specific adjustment needed in the workplace based on the load assessment. Further, this enables the adjustment of stress in a targeted manner with methodological or technological support. Thus it enables a systematic classification of technologies and methods for work design and work organisation considering the targeted relief of workers. Further, it provides the possibility to target the changes of performance prerequisites of employees by a structured search for possible solutions at different levels of action. Last, it provides suggestions on how the potential effects of different technologies and methods can be identified and critically reflected.

The result of literature and case research considering ergonomic interventions were summarized in an ergonomic intervention framework (Figure 68). For the differentiation of the determining factors for load reduction, the interventions are categorized into primary and secondary interventions. Whereas primary intervention deal with stress reduction, secondary interventions target the perceived work strain. As a second structuring element a division of measures in factors related to the production system, the external and internal exposure according to Westgaard and Winkel were chosen, which results in sub-categories for primary and secondary intervention measures. (Westgaard and Winkel, 1997) For the differentiation of the level of impact of measures an H-T-O structure (Karltun *et al.*, 2017) was chosen in accordance with the risk control hierarchy model (NIOSH cited from Liberati *et al.*, 2018).

The top level of the model shows possible sources of data to derive the base and prerequisites for each category. This data includes: workplace assessments, technology assistance profiles and qualification requirements for the technological interventions for the area of workplace design. In the domain of work organization, HSE management KPIs, job descriptions and process and procedure descriptions can serve as input data. For the human related area, data including the individual health status, load histories and ability- or qualification profiles should be used as input information. The interconnection of the three areas is shown by three indicators (intervention-workplace-, intervention-worker-, and worker-workplace-fit), which can be considered as the available target systems when searching for solutions. Within the intervention-workplace fit, it has to be checked if the intervention suits the characteristics of the workplace (e.g. available work tasks, feasibility for needed stress reduction) and work organization (e.g. cycle times, influences on other areas). The intervention-worker fit asks for a compatability of the intervention and the operator(s) (e.g. intervention for a single operator, for a special group of operators, or for a workplace, match with operator ability profiles). Finally, the worker-workplace-fit measures the fit of the intervention, the workplace and the worker in terms of the benefits provided for both by implementing the intervention.

The generalized and categorized measures together build the foundation for occupational measures and the ergonomic intervention processes that are meaningful in terms of physical stress reduction (general workforce) and strain reduction (specifically for an ageing workforce). This general structure can be used to derive fields of action based on ergonomic assessment results. Following the hierarchy of measures for OSH, the first target should be technical solutions, then organizational improvements and finally impact on worker level. Therefore, the horizontal axis in Figure 68 should be continuously followed from left to right, if no solution can be found in the previous category. However, this is not the current process in most improvement projects, as for the main part of measures the costs allocated for implementation will have an inverse trend.

According to the hierarchy of controls, exposure to stress should be first substituted and if this is not possible, it should be controlled and minimized by technical, organizational and personal measures (van der Beek *et al.*, 2017, p. 530). This means that interventions within the base for load reduction (vertical axis in Figure 68) should be continued from the top-down, if the previous section did not result in a possible or feasible solutions. While the first three categories in the load reduction base column ((re)design of work, change of job contents and limiting the exposure time) are primary interventions and therefore related to stress, the fourth category (conditions of execution) consisting of secondary interventions, is related to the perceived strain and therefore dedicated to ageing workers

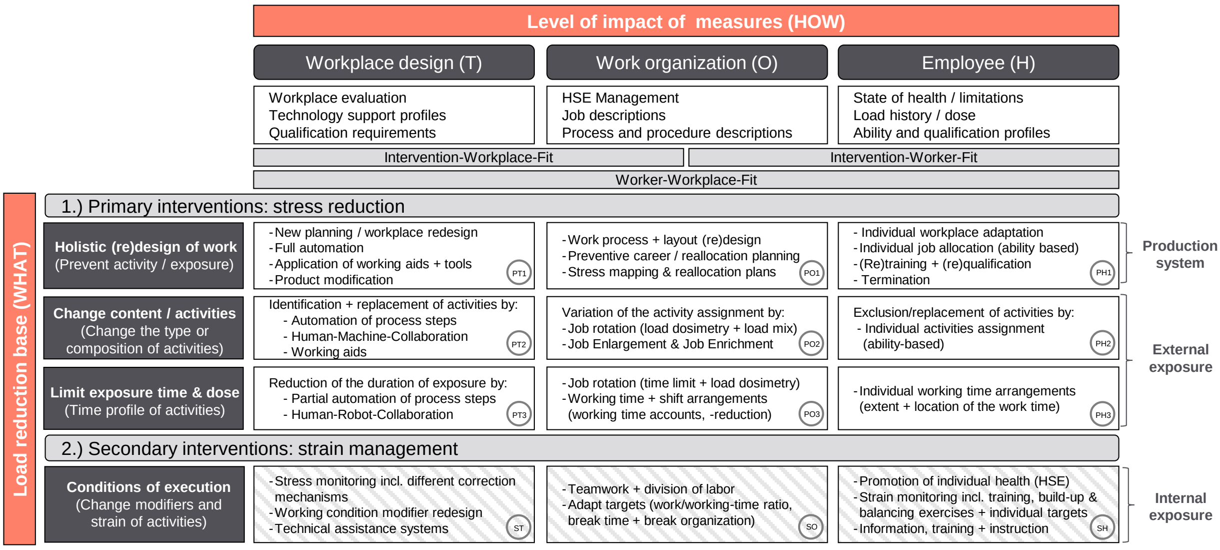


Figure 68: Ergonomic intervention framework (see also Apendix 4). Factors relevant for the eldely workers are highlighted in grey fields. For an explanation of the intervention abbreviations see main text and Table 23.

The framework in Figure 68 shows different measure clusters that can be used either for preventive planning, or can serve as a structuring element in searching a solution for an identified problem in terms of the workplace design. In terms of prevention, all categories can be useful. For work adaption, as reaction to existing problems, the framework should be followed from left top to bottom right, taking into account several different categories that can be useful. When searching a suitable solution for age-critical stress at the workplace, the fourth category includes suitable measures.

7.3.4 Derivation of fields of action according to the ergonomic assessment

The connection to workplace assessment can be derived by considering the individual composition of the risk factors. A classification of stress determining factors in product planning and production was derived by (Bierwirth, 2012, pp. 54–58). This classification can be used to identify suitable areas for measures, according to stress ratings.

7.3.4.1 Fields for action in relation to high energy expenditure ratings

For the energy expenditure in relation to working time related factors, the work processes and the system's degree of automation and mechanisation are relevant parameters. Focusing on posture and execution related aspects, the job content, the factory layout, the product design and the anthropometric design of the workplaces determine the energy turnover demand, according to existent climatic conditions. Finally, for all types of manual material handling tasks, the working energy expenditure is influenced by the weight of the loads, which is dependent on process design and load carrier sizes. Based on the risk level and the relevant influences, suggestions for suitable improvement measures can be derived according to the related risks calculation, which consist of time and posture, or movement dependent and task dependent factors, as shown in Figure 69.

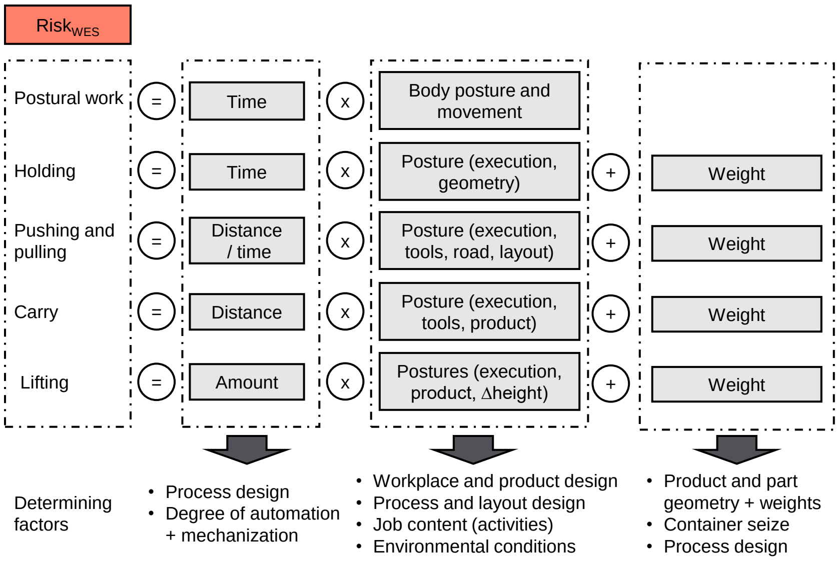


Figure 69: Calculation of the risk factors based on working energy turnover and related influences

A high work energy turnover indicates physically highly stressful tasks, so that a physical stress reduction is advisable. Workplaces with energy expenditure rates of over 8,400 kJ (~ 2,000 kcal) per work day (red category according to Table 4) require urgent workplace redesign measures as summarized in the intervention framework (Figure 68) in the first row under primary interventions in the technical domain (PT1). For working energy expenditures between 6,300-8,400 kJ per day (orange classification), also a complete redesign of the job considering automation and mechanization (PT2) is advisable. If this is not feasible, also time, posture, and weight related risk factors can be tackled, according to the suitable measures in the framework (PT3). For lower risk workplaces (yellow category), in addition to the measures already mentioned, also organization-, and human-related measures (PO1, PO2, PO3, PH3) might provide sufficient support to reduce the risk to acceptable levels and for green risk level workplaces personal measures (PH2) can be used voluntarily to further improve the individual working situation. The suggested measures according to working energy turnover are summarized in Table 23 enabling the selection of suitable area clusters per workplace and risk value.

Table 23: Ergonomic interventions for different energy turnover risk ratings. The labels stand for suitable measures of primary (P) and secondary(S) interventions in the technical (T), organisational (O) and human (H) area. The numbers (1,2,3) indicate the row-order in reduction mechanisms in the framework for primary interventions).

Risk index category	Risk =	Time x	(Posture +	Weight)
Red (>8400kJ)	PT1			
Orange (6300-8400kJ)	PT1	PT3	PT1	PT2
Yellow (4,200-6,300kJ)		PO3,PH3	PO1	PO2
Green (<4,200)			PH2	PH2

In relation to an ageing workforce, special attention should be paid to the working energy expenditure. If the result of the workplace assessment has acceptable risk levels in terms of energy turnover, elderly workers might still find themselves confronted with high strain according to the diminishing overall performance capacity. Therefore, the relative aerobic strain level provided by the assessment tool can be used to identify workplaces where age-specific measures might be necessary. Considering high RAS levels at green or yellow risk levels organizational (O) or employee related (H) measures improving the execution condition (S) are most suitable.

After inspecting workplaces for acceptable overall stress levels, a detailed examination considering the single risks deriving from physical workloads has to be conducted. Therefore, the standard and age-differentiated risk values provide the needed information in detail. Similar to the evaluation in terms of energy expenditure, first the age independent values should be considered and solutions can be identified in the intervention matrix according to the risk levels. Physical risk levels are calculated based on time-, posture-, execution- and weight-related factors. Suitable measures again cover the fields of process design, automation, and mechanization in relation to working time, the job content, product design, the anthropometric design of the workplaces, and the factory layout for posture related aspects and the weight of the loads, product and part geometry, process design and load carrier seizes for all types of manual material handling tasks. Further, the task risk is influenced by its execution conditions, where workplace and product design, environmental and climatic influences, and the degree of process binding as well as break time organization are the dominant influencing factors, as illustrated in Figure 70. Based on the risk level and the relevant influences, suggestions for suitable improvement measures can be derived, according to the related risks calculation consisting of time-, posture-, movement-, and task-dependent factors. High risk values in terms of posture or manual material handling indicate physical high stressful tasks, where a physical stress reduction is needed.

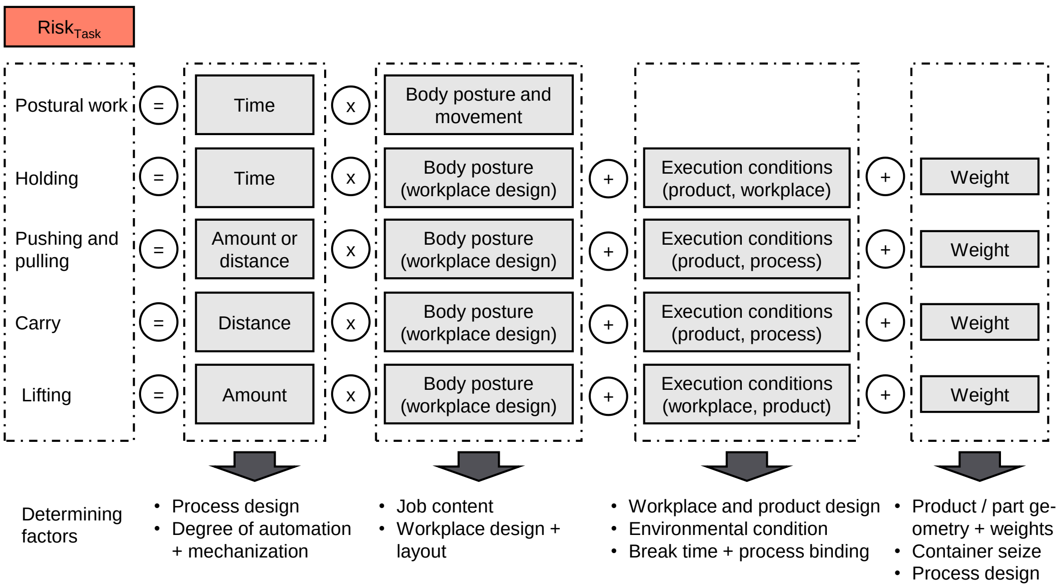


Figure 70: Calculation of the risk factors based on tasks and related influences

Intervention measures for task risk factors follows the same general strategy as for risks deriving from high energy turnover (see Figure 69 and Table 24 for details). According to the standard methodology of workplace assessment (see section 2.4.3), workplaces with risk values over 50 points (red risk level) require immediate workplace redesign measures, listed in the framework in the first row under primary interventions in the technical domain (PT1). For risk values between 25-50 points (orange risk level) also a complete redesign of the job, considering automation and mechanization is advisable (PT2). If this is not feasible, also time, posture and weight related risk factors can be tackled according to the suitable measure clusters in the intervention matrix (PT3). For lower risk workplaces (15-25 points, yellow), in addition to the already mentioned measures, also organizational improvements (PO) and enhancement of personal prerequisites (PH) might support in a sufficient way, to reduce the risk to acceptable levels. In addition, secondary interventions in the technical area (ST) might be perceived as useful at workplaces with high task related risk levels, especially in assisting body postures and reducing the perceived weight at load handling activities. Further, for improving execution conditions and for reducing strain at green-yellow borderline risk levels workplaces (15 points) technical secondary measures (ST) can be voluntarily introduced to further improve the individual working situation. The suggested measures according to physical stressful tasks are summarized in Table 24 enabling the selection of suitable area clusters per workplace and risk value.

Table 24: Ergonomic interventions for different task risk ratings (postural work and load handling). The labels stand for suitable measures of primary (P) and secondary(S) interventions in the technical (T), organisational (O) and human (H) area. The numbers (1,2,3) indicate the row order of reduction mechanisms in the framework for primary interventions

Risk index Category	Risk =	Time x	(Body posture +	Weight +	Execution)
Red (>50 points)	PT1		PT1	PT1	
Orange (25-50 points)	ST	PT1, PT3 PO1, PO3	PT1, PT2 ST	PT1, PT2, PO1, PH1, ST	
Yellow (15-25 points)		PT3, PO3 PH3	PT2, PO2 PH2, ST	PT2, PO2 PH1, PH2, ST	PH3, ST41
Green (<15 pints)				ST	

7.3.4.2 Fields for action in relation to high strain ratings

After ensuring acceptable risk levels according to a general energy turnover and task risk assessment of workplaces, age-specific factors have to be considered. If the result of the standard workplace assessment has acceptable risk levels in terms of physical parameters, elderly workers might still find themselves confronted with high strain according to the diminishing strength and endurance performance capacity. Therefore, the age-differentiated stress level provided by the assessment tool can be used to identify workplaces where *age-specific measures* might be necessary. In relation to the generally advised stress reduction, special measures for an ageing workforce should be taken at age-differentiated risk values between the orange-yellow (25 points) and yellow-green (15 points) intersections. Workplace conditions modifiers can be redesigned according to the need of an ageing workforce considering the measure clusters in Figure 68 for the age-differentiated risk values. Further, age-specific measures aimed at reducing the strain at workplaces with fixed stress levels are clustered in the secondary intervention section of the matrix. In general, these strain modifiers can be applied according to Table 25.

Table 25: Age-specific workplace interventions according to the age-differentiated risk assessment

Risk index Category	Risk =	Time x	(Body posture +	Weight +	Execution)
Red					
Orange					
Orange / Yellow	ST, SO	SO	ST, SH		ST, SO
Yellow / Green	ST, SO, SH	SO	ST, SH	ST, SO	ST,SO,SH
Green					

As shown in the previous section primary interventions for stress reduction can be beneficial for all workers in terms of high working energy expenditure levels and for high risk manual material handling tasks. Considering the ageing workforce especially secondary interventions that adapt the human to existing stress levels at workplaces have been identified as suitable solutions. Within this category, measure clusters include different types of interventions that can reduce the *perceived work strain*. In the application context of this thesis, especially technological assistance is under consideration. Therefore, no further investigations are conducted considering job organizational and employee related secondary measures and instead the focus is put on technological secondary interventions for reducing age critical work stress and strain, whereas especially assistance systems and technologies for the monitoring of work stress and strain are of interest.

7.4 STEP 4 - DEVELOPMENT OF MEASURES

A structured process to derive suitable measures according to the identified need and field for action consist of several steps that are explained in the subsequent section. The process developed builds on a DIMAC process as well (see section 6.3).

7.4.1 Generation of general solutions

As stated in section 2.4.4 the ergonomic improvement process is most efficient if conducted as participatory process. Therefore, in a first step, problems at the specific workplace and the accountable work stress should be identified, based on objective work place assessment results and subjective worker perception, involving the employees concerned. Therefrom, starting points to derive suitable measures can be tackled based on objective findings about possible solutions in alignment with the subjective need for assistance. As physical assistance systems mainly influence the perceived strain, a subjective evaluation of the prevalent work stress is a suitable starting point for the search for feasible solutions. A structured process for prioritizing work stress, according to perceived strain, should therefore focus on the opinion of the workers affected by it. Worker suggestions on workplace improvements should be gathered and specified by objective improvement suggestions. After gathering solutions by candidates, they have to be evaluated in terms of their potential to relief the worker in relation to stress and strain. After a suitable solution is selected, it has to be implemented, tested, and approved for industrial practise. If the solution is approved, it can be rolled out in the area. The participatory process developed is summarized in Figure 71.

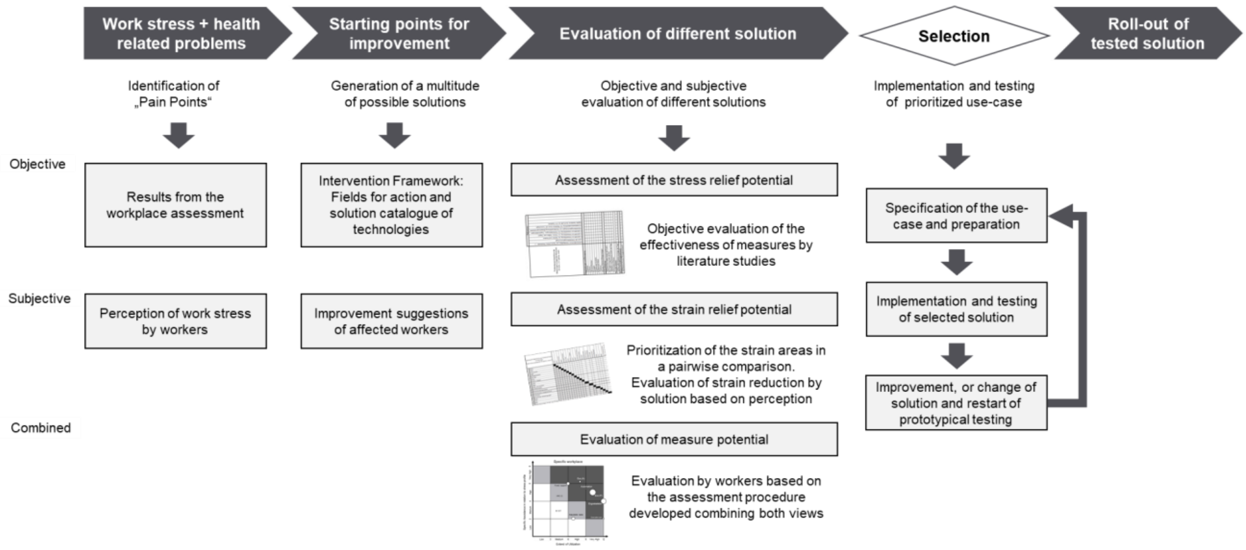


Figure 71: Process to identify suitable solutions in a participatory manner

7.4.2 Generation of specific solutions

To derive worker improvement suggestions a workshop concept has been derived (see section 4.2.2) including the presentation of workplace evaluation results, the discussion of physically strenuous activities, a root cause analysis of reasons for physical stress and effects and complaints of these work tasks. Based on the awareness built by this first discussion round, workers have to generate improvement suggestions for their workplace. This phase can be assisted with the use of different creativity techniques (see Higgins, 1994). As a structuring element for the clustering of measures, the categories of technical, organizational and person related measures of the intervention framework are used. The measures generated by the participants have to be analysed according to the type of intervention they represent. This enables the placement of specific measures in the intervention framework and thus a structuring of ideas, according to the selection framework. Thus, a structured process to find potentially suitable solutions can be conducted according to the intervention framework shown in Figure 68. Based on the requirement and the need for action a preselection of feasible solutions can thus be conducted.

7.4.3 Generation of technical solutions

Since the evaluation of possible benefits of phyical assistance technologies for age-appropriate workplace design lies at the core of this thesis an overview of such technologies had to be created. Based on available knowledge in literature (see section 2.5.6) currently available assistance systems were analysed and classified. A market analysis has been conducted and available technologies were evaluated in terms of benefits provided and possible challenges of implementation. The search lead to a structure of available assistance systems including a total of 45 different technology groups for work stress and strain reduction or control, that have been clustered into seven technology clusters. In Table 26 these main technical solutions for physical assistance in industrial blue-collar work are compared. This table briefly describes each system, its benefits and disadvantages and limits.

Table 26: Technical solutions for ergonomic improvement of workplaces (based on (Calzavara *et al.*, 2019, p. 10))

System	Description	Benefits and impact at work	Limits for the operator	Reference
Lifting and material handling devices	• Equipment that assists or helps the operator in moving and picking objects and parts • Assisting systems that neutralize gravitational load while holding tools (ZeroG) • Assistance systems for assembly e.g. arm stabilization, positioning of sub-assembly	• Increased efficiency and time savings for handling activities • Improvement and facilitation of assembly and picking activities (easier access, right mounting direction display) • Avoidance of musculoskeletal disorders and back pain	• Potential restriction of possible movements and placements in a certain area • System availability (failures could compromise worker operation) • Operators might become more stationary • Work processes might become slower	Karande and Chakraborty, 2013; Rossi *et al.*, 2013
Intelligent / smart tools	• Advanced active tool that is able to communicate and adapt itself to the environment of use, the operator and the product and with other tools	• Automatic tool calibration to the specific task • Waring in case of miss usage • Quality control: record of the operations and elimination of manual logging • Enhanced productivity: less time consuming (calibration, recording, fewer errors, information availability) • Possibility of real-time monitoring and data collection	• System availability (failures could compromise worker operation) • Job impoverishment	Takahashi *et al.*, 2016 Sauer *et al.*, 2014
Exoskeleton and Exosuits	• Technical device worn by the operator, which allows a direct exchange of mechanical power. It can be active (electrical) or passive (mechanical) or made from soft material (Ergo- and Exosuits)	• Ergonomic assistance for assembly, warehousing and handling activities (particularly for heavy lifting, prolonged standing, working in awkward positions like overhead work) • Physical effort, metabolic cost reduction (active) and lower risk for MSD • Reduction of work fatigue and therefor longer and safer productivity of operators • Longer and safer productivity of operators (long term)	• System weight and discomfort could reduce the operator's acceptability • Potential limitation in range of movement or mobility and speed • Knowledge about long term effects (health and safety) • System availability (failures especially active systems)	DeLooze *et al.*, 2016 Spada *et al.*, 2017 Hensel and Keil, 2018 Radder *et al.*, 2018 Linnera *et al.*, 2018 Keehong *et al.*, 2016 Parietti and Asada, 2016 Theurel and Desbrosses, 2019
Human robot collaboration (HRC), collaborative robots and human controlled robots	• Robot that can physically interact with the operators during assembly and manufacturing activities (i.e. handling and positioning of components)	• Simplification of tasks and activities through sharing of the content • Ergonomic improvements by taking over non-ergonomic activities (body postures, repetitive handling, manual material handling) • Space and cost savings due to sharing of the workspace • Increased safety when separation the operator from the hazard source	• System availability (failures could compromise worker operation) • Increased worker responsibility in terms of workplace safety • Ergonomics issues during the direct collaboration human and robots	Krüger *et al.*, 2009 Michalos *et al.*, 2015 Peshkin und Colgate 1999; Fast-Berglund et al. 2016
Smart and adaptable workstation	• Workstation with adjustable devices and systems, able to adapt itself to the operator's characteristics and needs. • Usually equipped with an active recognition system that captures and obtains the anthropometry of the worker • It can also include lifting and material handling systems	• Improved ergonomics (process efficiency and body postures) • Improved workplace wellbeing due to a personalised workspace • Greater system flexibility: different operators can use the workstations • Active assistance and feedback to operators during assembly processes (e.g. digital guidance, poke-yoke solutions) • Faster and more intuitive operator training and employment • Improved quality through proactive signals in case of error • Increased productivity through context related information	• System availability (failures could compromise worker operation)	Garbie, 2014 Kusiak, 2018 Gorecky *et al.*, 2014b
Systems for assisting work execution through (health) monitoring	• Monitoring of the ergonomic situation and current stress levels through cameras or sensors (i.e. activity tracker, smart watch, smart cloths)	• Improved stress and strain at work by the use of real time data concerning the physical state (heart rate, muscle activity and fatigue etc.) • Data can be used to suggest breaks or job rotation schedules, balancing exercises, personal limit values etc.	• Data privacy policies • Worker surveillance	Kasselmann and Willeke, 2014 Rönick *et al.*, 2019b Merino *et al.*, 2019 Walter and Mess, 2018
Wearable information systems (IKT) and augmented reality applications (AR)	• Use of technologies and devices to enhanced current perception of the reality (through graphics, videos, sounds or smart glasses, data glasses, projection technology etc.)	• Improved quality and error avoidance through proactive signals in case of error • Increased productivity through context related information • Reduced training effort for new operators due to assistance during the job • Improved ergonomics by system feedback in non-ergonomic work tasks • Active assistance and feedback to operators during assembly processes (e.g. digital guidance, poke-yoke solutions)	• Potential sight fatigue • Discomfort and additional physical stress (system weight if body-worn) • Job impoverishment • Pressure/stress due to high amount of information • System availability failures could compromise worker operation	Nee and Ong, 2013 Syberfeldt *et al.*, 2017 Kasselmann and Willeke, 2014 Stockinger and Zöller, 2019 Römer *et al.*, 2017 Apt *et al.*, 2018, p. 126 Theel, 2015 Gehrke *et al.*, 2015

7.4.4 Assessment of different solutions

The next step is an evaluation of the available solutions to identify the most suitable solution for high priority stresses. In order to assess the potential of different measures to provide such a relief, a benefit-analysis is a suitable tool. The measures should be characterised in three important dimensions: first, the benefits of the measure, for the reduction of stress or strain by provision of assisting functions in the specific application context has to be considered objectively and subjectively. Second, the extend of utilization of the system is an important framing condition. Third, the solution relevance as ratio of resources input to expected company-wide benefits has to be estimated to enable a comparison of the cost-benefit ratio. To narrow down possible solutions the measures can be prioritized according to these three criteria, preferring a high assistance potential and utilization as well as a low cost to benefits ratio.

7.4.4.1 Assessment of stress relief potential

To evaluate solutions suggested by the workers in terms of the first criteria a qualitative grading of the objective assistance provided can be conducted by an OHS expert. If solutions are searched based on the intervention framework the objective rating can be conducted based on literature studies. For such an objective rating, a process has been developed based on literature on physical assistance systems that can serve as a guideline to evaluate other solutions as well. To be able to evaluate solutions based on literature, a standardized description of measures is required. To this end, a template for conducting the objective analysis was developed as presented in Table 27. The aim of the description of measures is to support the implementation planning by showing examples of solutions in similar fields of application. The description of measures is structured in a way, so that the rating scales needed for solution assessment in section 7.4.4, can be completed with the information provided by the document. Information required for the evaluation are the general field of application of the system (1), the type of assistance provided (2), concrete examples applications of the system (3), a qualitative and quantitative description of the assistance provided (4), possible limitations that can arise by using the system (5), an estimation of the technological feasibility of the solution (6), an estimation of related costs for the solution and potential providers for the solution (6). Table 27 gives an overview of these criteria in relation to a specific example for each category based on the assessment of an passive exoskeleton.

Table 27: Template with description of the categories and exemplary assessment of the market analysis

Phase	Category	Detailed description of the systems	Example
Search for suitable solutions and evaluate general feasibility	Description	A short description of the system is provided	Supports workers in static postural work and dynamic load handling in back muscles
	Type of assistance	The type of assistance is defined according to the general phases of information processing (perception, cognitive processing and execution assistance	Execution assistance to reduce strain
	Visualization	The body region assisted is provided by a graphical representation	
	Example picture	An exemplary picture for a system can be provided to support imagination of the type of systems	
	Support provided	The type of support is defined in relation to the technology cluster	Physical support for lifting by exoskeletons
	Supported activities	A description of the supporting functions of the system in relation to different body postures (BP) and load handling (LH) is provided	BP: Bending LH: Lifting

Table 27 cont.: Template with description of the categories and exemplary assessment of the market analysis

Phase	Category	Detailed description of the systems	Example
Evaluate specific feasibility based on assistance need and performance	Assistance performance	The assisting function of the system is defined based on scientific testing or manufacturers product descriptions	• Reduction of back muscle activity for lifting by 10-48% and 44% on average for static postural work • Reduction lumbar moment by 20–30% • Reduction of compression forces at the lower spine by 12-29%
	Potential limitations and limits of applicability	Potential limitations of the technologies are listed to be considered in decision making	• System weight and discomfort could reduce operator's acceptability • Potential limitation in range of motion and work speed • Knowledge about long term health and safety effects
General conditions for implementation	NASA TRL	The technology maturity is determined as an indicator to enable an estimation of the expected duration for the integration or adaptation of an assistance system or technology. Market-ready products (TRL9) need the least effort for pre-implementation adaptions or development	TRL 9 (on market)
	Price category	The price category for the system is defined as a further criteria assisting the decision process for system implementation based on estimates, market prices or sample applications that have been carried out. This allows an early exclusion of costly solutions or an early inclusion of further measures to improve the cost-benefit ratio	Category 1 < 1000€ Category 2 1000-5000€ Category 3 5000-10000€ Category 4 10000-15.000€ Category 5 > 15000€
	Example manufacturer and products	Example manufacturers and products are named to identification for similar systems that might be suitable according to the specific industrial need facilitate later on the procurement	Laevo exoskeletons: Laevo V2

To assist the industrial application of the assessment of objective benefits provided by different physical assistance technologies, all the technologies gathered have been evaluated according to the standardized structure introduced in Table 27. The result of this process is a specific solution catalogue of current technologies to reduce physical and cognitive work stress. An example of a specific technology and its assessment is given in the last column of Table 27 for a specific exoskeleton. The catalogue for all systems is provided in Apendix 5. Based on the workplace evaluation results these technology profiles can be used to determine suitable systems in accordance to the stress relief potential and prevalent stress profiles. However, as the assistance provided by each systems strongly depends on the task-technology-fit (see section 2.5.7) which is partly based on the objective assistance provided and partly on user perception of the system, a qualitative grading of the technologies has been conducted as well. The grading is based on the literature studies mentioned in Table 26, the results of the market analysis, and on expert ratings provided in the course of the conducted field study.

The assessed literature and expert ratings of the different clusters revealed that automation provides the ability to prevent all types of work stress, by separating the worker and the task. However, automation is in many cases technologically not possible and in a far larger amount of cases economically not viable. Further, the application of working aids and tools showed high relief potential, as these technologies can be specifically designed for the required assistance. High potential of working aids and tools has been reported especially for manual load handling activities, where balancer, cranes, lift trucks etc. are available for affordable costs and totally separate the worker from the potentially harmful stress. Also in terms of awkward body postures and frequent bending working aids, as rotating work piece holders or height adjustable platforms and static body supports, offer a great potential for stress reduction. However, most of this solutions provide low level of flexibility for very dynamic working conditions due to their static nature. Lower potential for reducing work stress and strain has been reported in terms of human robot collaboration (i.e. collaborative robotics) and individually adjustable workplaces. Cobots can offer some substantial assistance in repetitive manual assembly tasks, by sharing the job content with the operator. Thus, ergonomic improvements can be achieved by transferring non-ergonomic activities (body postures, repetitive handling, manual material handling) to the system. Further benefits of such systems were reported for increased operator's safety, if the source of hazard is separated from the operator's area of effect. In comparison to automation technology, cobots also offer increased adaptability and flexibility considering the work tasks, as well as space- and cost saving possibilities due to sharing of the workspace. However, they also provide lower potential of relief in all categories of work stress. The same applies for adjustable workplaces, which offer most benefits for static postural work, as in preventing static standing and bending. Here, ergonomic improvements can be achieved by adjusting work places to individual characteristics and preferences. Further advantages of such systems are seen in improved wellbeing due to customization and the enhanced flexibility in terms of ergonomics and different operator's characteristics. Nevertheless, same as for automation and mechanical working aids, also smart and adjustable workplaces are locally bound and thus suffer from limited flexibility in dynamic work environments.

As already mentioned in section 2.5.11 the technology of exoskeletons provides a decent potential for the reduction of perceived strain in highly varying and dynamic tasks, especially in relation to load redistribution in manual material handling and reduction of loading of specific muscle groups in postural work. The following differences have to be considered for active (A) and passive (P) systems: Active systems generally provide higher support in material handling tasks and might be beneficial in reducing metabolic cost of workThrough active muscle and movement assistance they provide the most benefits in terms of ability limitation. Passive systems provide lower amount of assistance for material handling, but are especially beneficial in assisting static and dynamic body postures. The same applies for ergo-skeletons, which are usually light-weight passive exoskeletons. In either case, active as well as passive assistance can reduce work fatigue and enable longer and safer productivity of operators. Therefore, caused by their flexibility and support functions, exoskeletons are feasible solutions for dynamic and variable work as prevalent in assembly, warehousing and production activities.

Generally, a lower amount of information in terms of physical stress or strain reduction capability is available for information and communication technologies (ICT) and digitally enabled systems to record work strain and support in proper work execution. Based on information from industry and the few reports available, both types might have positive impact on work strain reduction, considering the avoidance of unnecessary work, e.g. unnecessary walking while searching for an inventory place (ICT), or better ergonomics through real time system feedback and a better distribution of work tasks or load to people, based on real-time values generated by the system (tracking technology). Nevertheless, benefits of ICT and tracking technology have been reported in relation to active cognitive and sensory assistance, faster and effort-reduced training, quality improvement, enabled by error prevention through worker surveillance and increased productivity by providing context based information. The qualitative rating of physical relief potentials of the different technology clusters, based on literature and expert ratings from industry is summarized in Figure 72.

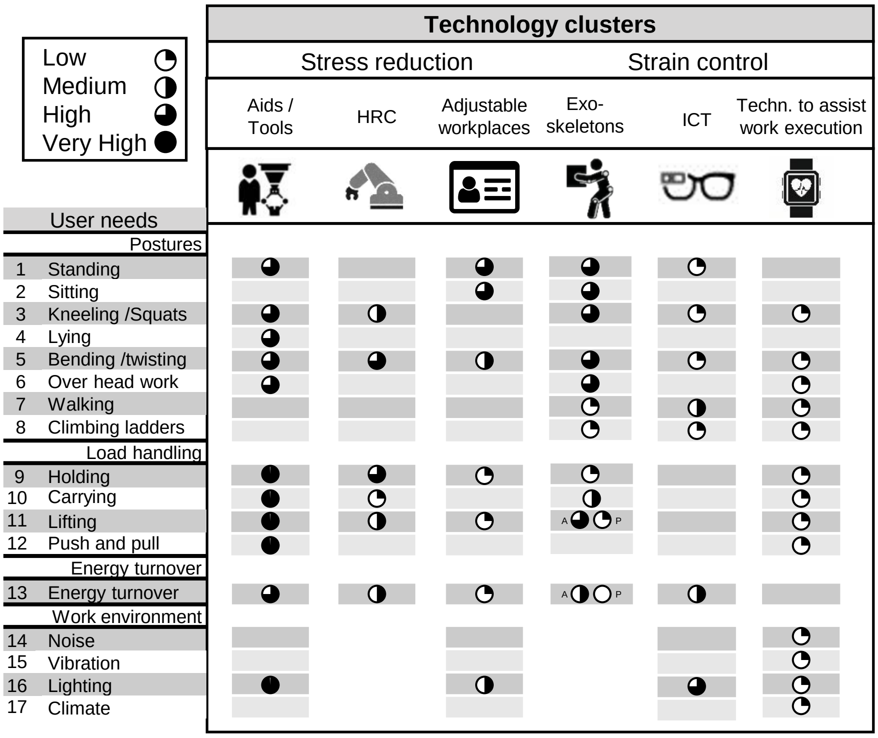


Figure 72: Qualitative assessment of relief potential of different technical solutions to reduce physical work stress and strain. For the exoskeleton category A (P) refers to active (passive) systems.

7.4.4.2 Assessment of strain relief potential

As age-differentiated workplace improvements with physical assistance is strongly related to the perceived strain, worker perceptions have to be included in the assessment. To include worker perception in the decision process, a measure evaluation has to be conducted including a prioritization by stress type and magnitude. For the prioritization according to prevalent work stress a subjective preference analysis by means of pairwise comparison is a suitable tool. From the results of such an analysis, subjective weighting factors according to the severity of perceived stress can be derived. In this method workers compare two elements of work stress and have to judge with one they perceive as more stressful. This easy method is thus suitable for a quick weighting of stress factors according to workers' opinion. An exemplary table for a pairwise comparison is shown in Table 28.

Table 28: Exemplary pairwise comparison of types of work stress

Workplace: ----------------------- (Row higher than column 1, else 0)		Sitting	Standing	Keeling		Holding	Lifting	Sum	Weight
1	Sitting		1	0		0	1	2	20%
2	Standing	0		0		0	0	0	0%
3	Kneeling / squatting	1	1			0	0	2	20%
12	Holding	1	1	1			0	3	40%
13	Lifting	0	1	1		1		2	20%
Sum									100%

By comparing the elements of the ergonomic workplace assessment procedure, one by one, and summing the relative frequency of perceived stressfulness per task, the weight of the specific task can be calculated. The result of this process is a subjective ranking of workplace related stress and can be used to determine stresses with high need for relief at the respective workplace.

To evaluate the subjective benefit and the task-technology-fit, a grading by the workers can be conducted. As the subjective task-technology fit is strongly influenced by the perceived utility and benefits of using the system (see section 2.5.7), also a subjective rating of the expected assistance, in the specific application context by the intended worker population is necessary. According to the ATD selection framework decision making on a specific measure should be based on objective and subjective needs. The objective need for assistance can be derived from the ergonomic assessment of the workplace and the subjective need can be analysed using psychophysical grading scales (Borg, 1998) for comparing with, and without system condition. The assistance provided by different measures can be evaluated with subjective grading scales in a utility analysis, or by a general subjective grading. As the specific assistance is highly dependent on workplace characteristics the systems have to evaluated in relation to those, which can be best conducted by the operators of a specific workplace. For the evaluation of these two items an objective-subjective evaluation is required to derive the workplace specific assistance of a technology in relation to a specific need for assistance or more precise, the subjective measure-operator-task-fit, i.e. the user evaluation as surrogate (see section 2.5.7) for the specific application.

7.4.4.3 Overall assessment of the relief potential

To combine objective and subjective grading, the assistance provided by the system is translated to the four fold grading scale according to the Table 29. For the objective grading the levels of low, medium, high, and very high can directly be transferred from the qualitative assessment of relief potentials of assessed technologies. For other measures these criteria have to be evaluated by industry experts according to the provided rating scale.

Table 29: Practice-oriented rating scale to evaluate the objective and subjective specific task-measure fit and the relief potential named as specific assistance (full rating scale in Apendix 6)

Assessment sheet		Points				Solution 1
		Low (1)	Medium (2)	High (3)	Very High (4)	
Provided specific assistance						
1	**Objective task-related performance**	None or little assistance provided	Medium assistance provided	High assistance provided	Very high assistance provided	
2	**Subjective measure-workplace-fit**	System provides low benefits in relation to tasks and workplace	System provides medium benefits in relation to tasks and workplace	System provides high benefits in relation to tasks and workplace	System provides very high benefits in relation to tasks and workplace	
					Evaluation result A= sum (1-2)	

To assess the benefits of a solution, the extend of utilisation of a system, is the second dimension of the assessment. The extend of utilization of a measure is a combination of the following three areas: (1) number of users that can benefit from the solution, (2) the frequency of use of the system in relation to activities at the workplace, and (3) the fields of application of the specific measure in the work area. For the evaluation of the extend of utilization a practice-oriented rating scale is shown in Table 30.

In the first part of the evaluation, the specific assistance of the system is calculated as the sum of line one and two, and the extended of utilization as sum of line 3 to 5. The combination of these two values corresponds to the specific benefits of a measure, calculated as the multiplication of the two results. Based on the grading system the specific benefit can take values of 6-96 points, whereas values from 2-25 points correspond to a low, 26-49 to a medium, 50-73 to a high and 74-96 points to a very high perceived assistance.

Table 30: Practice-oriented rating scale to evaluate the expected extend of utilization

Assessment sheet		Points				Solution 1
		Low (1)	Medium (2)	High (3)	Very High (4)	
Extend of utilization						
3	**User group**	One person	Small group of users	Medium group of user	Large group of users	
4	**Frequency of use**	Rare application for special tasks (< 10% of working time)	Average frequency of use (10-50%)	High frequency of use (50-80%)	Permanent application for all tasks (> 80%)	
5	**Fields of application**	Only for the special activity (<10% of tasks)	Some other possible activities (11-40%)	Several possible activities (41-70%)	Many possible activities (>70%)	
					Evaluation result B = sum (3-5)	

The third important criterion to compare different solutions is the specific relevance of the measure within the company's context. This criterion includes the management perspective into the evaluation of different feasible solutions by assessing the overall impact of the measures based on a benefit to cost perspective. According to Drucker 1986, the main three tasks of management in industrial companies are to manage economic profit by taking appropriate decisions and actions (1), to make human resource productive (2), and to manage social responsibility of the enterprise (Drucker, 1986, pp. 32–33). Thus, for the management perspective, framing conditions include the creation of situation awareness, clear indicators for decision making, the identification of a need for action considering productiveness of ageing workers and a structured process to provide safe and healthy working conditions throughout the working life, to meet the social responsibility aspects. Thus, a prioritization strategy for appropriate measures in the fields of action is needed. Further, in this perspective long-term and aggregated information is needed for strategic decision making and approximations are acceptable (Anthony, 1965, p. 93). From an operations perspective, the focus is on a specific task and its improvement. Usually clear rules are followed to derive rational decisions and company tailored, detailed and precise information are considered.(Anthony, 1965, p. 93) Hence, framing conditions on operational level include clear and structured processes and industry tailored tools, that can be applied with a low time input for the evaluation and improvement of working conditions. Therefore, first, the solution profitability is evaluated as a combination of the specific benefit for the problem at hand and the transferability of the solution to other areas and issues within the area of consideration. The practice oriented rating scales for profitability is provided in Table 31.

Table 31: Template for an practice-oriented rating scale for the assessment of the solution profitability

Assessment sheet		Points				Solution 1
		Low (1)	Medium (2)	High (3)	Very High (4)	
Solution profitability						
6	**Benefit of the solution (Result A x Result B)**	6-25 points	26-49 points	50-73 points	74-96 points	
7	**Transferability of solution to other areas**	The case is unique within the company	The case is transferable to a few other areas	The case is transferable to several areas	The system can be transferred to most other areas	
					Evaluation result C= sum (1-2)	

Second, the expenses needed to implement a specific solution are to be considered. Here a distinction is possible in the sub-dimensions of technology availability, which can be determined based on the technology maturity (technology readiness level, TRL) and the transfer effort needed for the specific application, and the internal resources (working time) needed for adaption and implementation, as well as the acquisition costs for the intervention. The practice oriented rating scales for profitability and expenses are provided in Table 32. As the quantification of costs is a very company specific criteria, it is to be conducted for each application individually, and the grading scale is thus not specified.

Table 32: Template for an practice-oriented rating scale for the assessment of resource input for different solutions

Assessment sheet		Points				Solution 1
		Low (1)	Medium (2)	High (3)	Very High (4)	
Solution expenses						
8	**Technology availability (procurement and transfer)**	Supplier and examples on the application in the specific context are available (TRL 9)	Supplier and examples on the application in other use cases (TRL 9)	Information on application of the technology in other use cases (TRL 8-9)	No information on application of the technology in use cases available (estimate effort based on TRL)	
9	**Internal use of resources (working time)**	Plug and Play purchase of a customized solution	Little need to adapt existing solutions to the company specifics	Need for bigger adaptation of the solutions to the company specifics	Creation of a new individual solution	
10	**Acquisition costs**	Low costs (<___ €)	Average costs (___ - ___ €)	High costs (___ - ___ €)	Very high costs (> ___ €)	
					Evaluation result D= sum (6-8)	
					Solution relevance = Result C / Result D	

The derived numbers can be used to calculate the potential of a technology and compare it to other feasible solutions, by dividing benefit-related and effort-related numbers (Spillner, 2014, pp. 77–78). The solution relevance is calculated as the benefit-cost ratio by dividing the profitability (evaluation result C) to the related expenses evaluation result D). According to the grading systems values of 0.17-2.67 point can result, where a higher value corresponds to a greater potential for the use of the technology. The ratio thus favours practicable solutions by taking into account costs and availability.

7.4.5 Selection of a solution cluster

To interpret the results of the assessment process, a solution priority matrix can be generated based on the evaluation. Such a matrix offers several benefits for occupational practice. First, it provides aggregated information about all three relevant criteria of solution assessment, thereby enhancing decision making. Second, it enables the comparison of different solution and reveals solutions that might be technically advantageous, but would not be accepted by the operators and vice versa. Third, if a certain amount of assistance is defined for a workplace, e.g. based on an ability limitation of a worker or a workplace stress reduction goal, this threshold can be easily implemented as filter in the priority matrix. Hence, this type of visual result representation is particularly useful for a selection of the technology for subsequent implementation for testing.

To create the priority matrix, the aggregated values of specific assistance potential and perceived extend of utilization for the selected tasks are transferred into the matrix on the vertical and horizontal axis respectively. As a secondary decision supporting criteria the solution relevance is presented as the seize of the marker, whereas higher relevance is represented by bigger markers. Therefore, the numerical value of the solution relevance is used to scale the relevant marker to the according seize. As a prioritizing rule solutions with a high assistance potential and a high extend of utilization are preferable. Within the high potential solutions (dark grey area in the chart), a decision should be made according to the highest solution relevance which meets the objective need for assistance

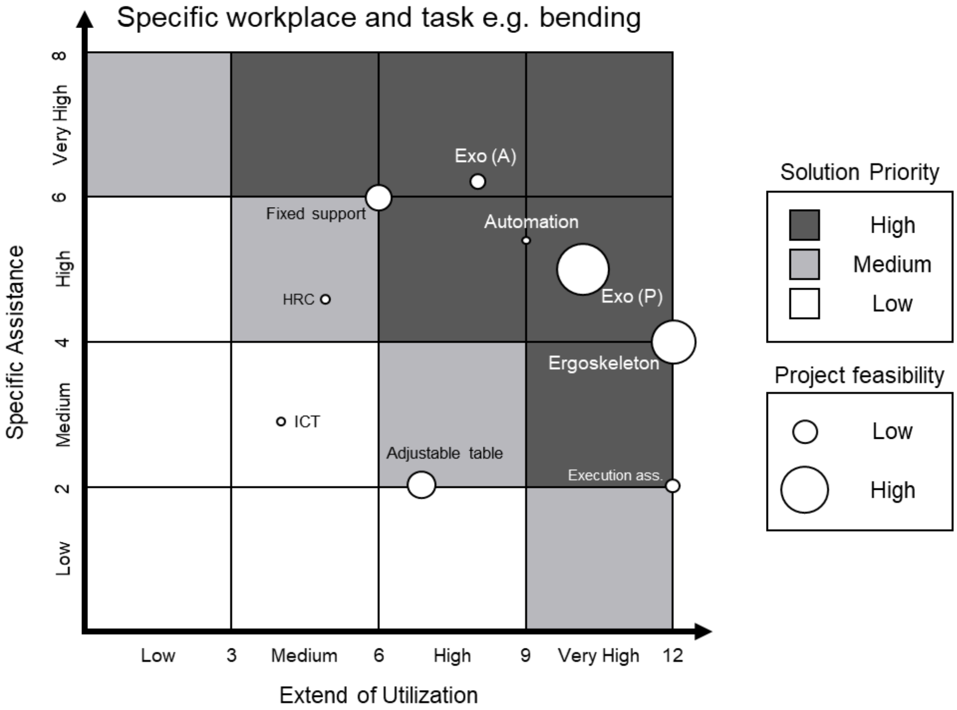


Figure 73: Priority matrix for different solutions in relation to a specific task

To determine the minimum assistance needed a transfer of workplace evaluation results in the suggested priority matrix and the identification of the most suitable tasks is needed. The objective need for assistance can be expressed as numerical value according to the ergonomic assessment of work places. However, such a formulation proved to be not feasible for the industrial partners. To meet industrial requirements, a formulation according to the grading system was derived, to easily integrate the objective need of assistance in the evaluation matrix. Therefore, the objective need for assistance is expressed in relation to the minimum reduction of risk level required. Reducing the level by one grade (e.g. from yellow to green) relates to the grading of low assistance. Reducing the risk by 2 levels refers to a medium assistance level. A reduction by 2-3 and more than 3 levels is associated with high and very high assistance, respectively. This assumption is permissible in this context, as the assistance illustrated in the chart already considers the specific subjective support by the technology within the application context. Thus, based on this grading of the objective need for assistance, the minimum assistance required for the workplace can be determined and used as filter for the priority matrix. In relation to the extent of utilization of a technology the minimum threshold for the implementation of a new measure or technology is hard to define on a general level. It strongly depends on the companies' culture and lived habits and values. Thus, the definition of minimum acceptable perceived utility is an optional filter to implement in the priority matrix. Generally, values within this category should be located at the high or very high grading category, to ensure a successful change process and a high utilization of the implemented measure by the working population.

Based on the priority matrix in combination with minimum threshold values suggested, a management decision can be conducted based on objective criteria of the workplace assessment, determined for the specific task under consideration. This can either be stress reduction through workplace (re)design, activity sampling or time limitation, or alternatively strain control by secondary interventions. Applying this context, the suggested measure framework for current technology clusters can be used to identify suitable technical solutions for different general work tasks, and the suggested workshop setting can be used to derive additional company-specific measures that are beneficial for the specific use case. The second criteria, the perceived feasibility of the measures, is an evaluation of worker perception of related benefits and includes a subjective indicator for worker acceptance, thus representing a surrogate for a task-technology-fit indication. By means of the evaluation process derived, all measures can be evaluated and transferred to the solution priority matrix, which enables an objective management decision, based on qualitative data.

7.4.6 Identification of the specific measure

Based on the selected technology cluster a specific measure has to be selected and detailed. First, a make-or buy decision for the measure has to be taken. The specific requirements for the measure can be derived from the workplace assessment, need for assistance and the evaluation criteria. Based on the requirement profile a specific technology has to be developed, chosen from the technology catalogue or be enquired at different manufacturers. When detailing the specific technology or measure, worker specific characteristics (anthropometry, skill, preferences, etc.), technology related specifics (assistance profile, assisted tasks, ease of use, training needed, comfort, limitations of movement, etc.) and work place specific factors (load and posture characteristics, and work space features, environmental features, etc.) should be taken into account (see section 2.5.7). Based on these considerations several possible systems have to be compared and the most suitable solution has to be identified.

7.5 STEP 5 - VERIFY AND CONTROL

The last phase deals with a validation of the selected solution in relation to the real application context. Therefore, first a plan for the implementation has to be generated and second, the impacts and the effectiveness of the solution has to be tested in a pilot implementation area.

7.5.1 Implementation and conduction of the testing

For the implementation and testing of technological benefits, a detailed plan for implementation is required. This plan includes a project setup according to a project management improvement cycle. The detailed planning includes preparing of the implementation, procurement of the measure, scheduling of the testing and preparation of the workforce. While the first two steps can be considered as pure project management tasks, the preparation of the workforce is a crucial step for successful implementation and testing. This process should include the relevant parties (occupational medicine, worker council and social leaders in the workforce) to ensure a broad acceptance and willingness for testing. Preparation can be best conducted in a workshop setting where all involved parties are brought together and the intended benefits and related needs are clearly communicated. Critical steps include the securing of a high voluntary participation, safety aspects during testing and treatment of partially sensitive data.

7.5.2 Assessment of impact and effectiveness

To evaluate the impact and effectiveness of a solution, a standardized and scientifically grounded procedure is necessary. Therefore, a structured testing procedure and test design have to be developed and suitable testing methods have to be compiled. In terms of the testing process, an approach according to the one developed for this study can be followed. According to Jawad *et al.* an implementation of physical assistance systems should follow a process that includes the steps of selection of a solution (1), conduction of a pilot-study (2), verification of the basic function and worker’s reactions (3), and the execution of a long-term testing for initially positive evaluated technologies (4). This process is to evaluate potential negative side-effects that were not apparent in the pilot study (Jawad *et al.*, 2019). For short term testing the questionnaire developed for this study (PRE Apendix 7 and POST Apendix 8) can be used to assess the impact of physical assistance systems on work strain. When required, it can be adapted to specific needs. Also for long- term testing a questionnaire approach based on the developed testing tool is possible. For long term testing however, the reassessment of the work situation after a testing period of three, six and more months using the PRE questionnaire for evaluating changes in physical complaints is advisable. In addition, the multiple evaluation of strain reduction based on the POST questionnaire (Apendix 8) might be considered to evaluate long term perception changes of the strain reduction by the technology.

After successful testing the results of the survey have to be evaluated and compared against a target outcome. The evaluation should focus on the perceived physical strain reduction in different tasks or in relation to different body parts (in terms of existing workforce limitations). Further, the workforce’s reaction to the device is an important indicator for later usage of the device. If both, the assistance and worker’s acceptability of the device, meet the expected demands, the solution can be considered as field-approved. In case that one or both of the criteria are not met, a redesign of the solution according to the needs identified during testing, or a change of the solution and retesting, according to the priority matrix has to be conducted.

7.5.3 Develop a roll out plan and consolidate and document

After a successful short- and long-term testing, the roll-out of the measure can be planned and conducted. Critical factors to consider are the amount of systems required and issues related to the broad utilization of the technology. In relation to the amount of systems required, the user group has to be defined. In addition, the allocation of the systems to the workers (one system per worker, shared use, etc.) has to be defined and aligned to work system requirements (time of using the system per shift, amount of workplaces where the system is applicable, adaption needed at the workplaces for efficient system used.). In relation to the technology itself, handling factors (hygiene, cleaning of the system, time for recharging, etc.) and safety aspects (instruction, safety training, safety documentation, etc.) are important to take into account. If the solution is considered as field approved, the benefits of implementing the solution have to be documented. Therefore, the results have to be included in the overall ergonomic assessment of the workplace. As there is no current standardized ergonomic assessment method that is capable to properly evaluate the effects of technical devices for strain reduction, further research is needed to develop such a procedure. However, the assessment of the systems as suggested in this thesis can serve as technology profile for strain reduction and can be used to estimate the achieved stress reduction, as introduced in the next chapter. For documentation, the relief profile of the system should be stored and the technology catalogue of feasible solutions should be updated with new best practice examples if they have been successfully tested and implemented

8 DISCUSSION OF RESULTS

In this section the results of this thesis are discussed based on a prototypical testing conducted during the research project. Based on the results, the scientific rigor and practical applicability, as well as the benefits for practice are outlined for the methodology for age-differentiated workplace assessment, and the selection process developed. Finally, conclusions on the procedure model are drawn based on the application of its building blocks in industry and the achieved contributions for scientific literature and practise are drawn.

8.1 VALIDATION OF DEVELOPED TOOLS AND PROCESSES

This section discusses the validation of the building blocks of the procedure model and outlines derived conclusions of the results for the overall management process. The process quality of the model is proven based on the validation of the developed tools with the industry partners. The validation of the developed tools refers to its validity, objectivity, reliability applicability and acceptance of results.

8.1.1 Discussion of the procedural quality of age-differentiated assessment tool

To examine the procedural quality and outcomes of the age-differentiated assessment tool a prototypical application was conducted in both case companies at 13 workplaces in manufacturing and assembly departments and 11 workplaces in logistics and retail jobs. Different departments, job types and activities were sampled according to the two main physical stress types considered in the assessment to provide a holistic overview of the applicability of the tool. In total 208 work activities were captured and observed by the author of this thesis in on-site observation interviews. The observations were documented in observation protocols specifying the relevant input parameters for the assessment procedure. Based on the observation protocols, the newly developed tool was used to evaluate the age-differentiated risk values. The results obtained by the assessment were discussed in a workshop per company with industrial experts comprising occupational medicine practitioners, occupational physicians, health and safety officers, industrial engineers and worker council members. Further, the evaluation results were compared against the perception of the task by workers in an additional workshop per company.

The evaluation of the process quality of an ergonomic assessment procedure can be discussed based on general quality criteria of validity, objectivity, and reliability (Döring and Bortz, 2016, pp. 442–447; Creswell and Creswell, 2018, pp. 153–154). Further, as it is intended to provide benefits for industry, the criteria of applicability and effort for analysis and evaluation in operational practice, acceptance of the process results by practitioners, and the limits of the process application are of interest. The process quality of the developed tool has been discussed with industry experts and validated against worker perception. Findings of this process are outlined to discuss the process quality of the developed tool on the basis of the criteria mentioned.

8.1.1.1 Validity

The methods validity indicates if the method measures the intended criteria (Döring and Bortz, 2016, p. 446). Different main approaches of determining validity in relation to work analysis methods exist (Oesterreich and Bortz, 1994). Validity can be established in an objective way by calculating correlations of assessment results. Such an evaluation includes the assessment of single tasks with different methods and a cross comparison of results to identify significant correlations or differences. This implies that a multitude of measurements with different methods are necessary to show statistical significance. Since comparable methods do not exist, this validation is not feasible for the current tool. However, as the developed tool builds on existing industry standard tools, that are not necessarily scientifically validated themselves, but considered as state of the art, comparing the results without consideration of age-differentiated values can serve as a proof of validity and suitable operationalization of the tool. The validity of the assessment procedure is secured by the combination of industry approved tools, namely, the key indicator method and the ergonomic assessment worksheet with tools that consider age-related ability decline (REFA method) and individual abilities (ERGO-FWS). The validity for the modelling of age-based decline of abilities is secured by an in depth examination of related available literature and modelling of the decline based on established scientific results (cf. sections 2.3.1, 2.3.2).

In relation to the modelling of the relevant influencing factors for age-related ability decline in relation to the tasks and not in relation to specific abilities, it is assumed in the model that a decline in physical strength moderates the lifting risk and a decline in static endurance influences the risk of postural work. This assumption is based on findings in literature which, however, are not sufficiently detailed to provide validity to this step. Here, a different approach to prove validity is to be conducted. Alternatively, method validity can be determined by measuring physical outcomes in relation to work tasks and establishing significant correlations, or by means of experimental investigations which prove effects of certain workloads in regard to other measurable characteristics. However, to derive age-related health outcomes a longitudinal study design over many years is necessary. In addition, since the measurement of age-differentiated strain as a result of workload involves increased effort, this type of validation is also not applicable here. Thus, only a subjective determination of the validity of the procedure by a representative number of experts as suitable for ergonomic assessment methods (Oesterreich and Bortz, 1994) can be conducted. To evaluate the extent to which the method and its features accurately capture reality, or whether the construct under investigation has been adequately operationalised, the results of the procedure were discussed with experts from occupational medicine and industry experts. The validity of the criterion of overall physical capacity expressed as decline in maximum oxygen consumption, the evaluation of energy sales related risk were approved as suitable for the intended use of the tool by all industry experts included. The same applied for isometric physical strength for general consideration of holding and carrying, back muscle lifting strength for lifting tasks, and static endurance of back muscles as overall criterion for postural stress. However, to allow for a more detailed assessment, additional criterions are required for scientific validity and further validation against health outcomes is necessary.

8.1.1.2 Objectivity

The objectivity of a procedure is used to assess whether the implementation, evaluation and interpretation of the results is independent of the user (Döring and Bortz, 2016, p. 443). Accordingly, three sub-forms of objectivity can be differentiated (Moosbrugger and Kelava, 2012, p. 8). First, the objectivity of implementation is ensured if the test result is not influenced by the person conducting the test. Second the evaluation objectivity is given if the process results remain uninfluenced by the evaluator. Thirdly the objectivity of interpretation is given if process users come to the same conclusions based on clear interpretation rules.

the objectivity of implementation is ensured if the test result is not influenced by the person conducting the test. Second, the evaluation objectivity is given if the process results remain uninfluenced by the evaluator and, third, the objectivity of interpretation is given if different users come to the same conclusions based on clear interpretation rules.

As mentioned in chapter 5, issues regarding the derivation for suitable values for the assessment were identified separately in both companies due to low degree of standardization. To enhance objectivity in such situations, the tool was designed in a way where the whole working day is modelled for the worker. This ensures that all stress factors mentioned by the worker can be included in the assessment. If the procedure outlined in this research project is followed, a high degree of objectivity in the assessment can be reached. This is due to the fact that the process follows a three-step approach, where in the first step, based on the worker survey data sheet, physically most stressful tasks are identified per workplace. This tasks build the base for the second step, where the workplace is visited. In the site visit, a targeted observation and measuring of the most stressful tasks per area can be conducted and documented in the workplace observation protocol. Further informations regarding low stress work tasks can be obtained by interviewing the worker. In the third step, the observation protocol can be easily transferred to the evaluation tool in excel searching for the suitable type of stress and workload defining characteristics (see section 7.2.3). This process offers several advantages: First, it ensures that the relevant tasks are covered in detail and only information for task perceived as low stress tasks have to be estimated by the worker or the conductor of the assessment. Second, the observation interviews revealed that for low stress tasks, worker estimations of workload characteristic were more accurate as for high stress tasks. Third, based on the observation protocol in combination with the results of the worker survey, a common interpretation among different involved persons can be achieved by relying on the gathered data. Fourth, in the evaluation phase, different persons conducting the assessment will derive very similar results with the excel tool when conducting the assessment based on the same protocol. Thus, the influence of the person conducting the assessment, as well as, personal influences on results are limited. This is due to the standardized and structured procedure and the predefined categories in the tool that are aligned with the observation protocol sheet. Finally, the results are presented in numbers and classified according to the commonly used traffic light evaluation scheme, as aggregated overall workplace values with clear rules for deriving the need for action. Thus, the results are presented with clear interpretation rules limiting the operators influence in interpretation. In summary, overall a high objectivity can be assumed for poorly standardized task, if the three step approach is conducted.

8.1.1.3 Reliability

Reliability is established when repeatedly application of a tool provides similar results (Moosbrugger and Kelava, 2012, p. 12). Reliability is differentiated in interrater reliability where different test persons conduct the test, and retest reliability, where the same condition is tested at two different times (Moosbrugger and Kelava, 2012, pp. 11–12; Döring and Bortz, 2016, p. 444). For the verification of the reliability of condition-related analysis procedures Oesterreich and Bortz, 1994 propose double and repeat analyses. In a double analysis, a work activity performed by different employees is analysed by different users of the procedure. In contrast, in a repeat analysis, a work activity is performed by only one person and repeatedly analysed by several evaluators. Double analysis has been tested once based on observation protocols for the age-differentiated assessment tool. Therefore, the results obtained by the author of this thesis were compared to the results of an industrial health officer applying the tool for the same observation protocol. Based on the clear rules for the input in the excel tool and the linkage between the observation protocol and the tool all risk ratings were of the same category by this test. Some issues the occurred during testing which lead to an adaptaion of the procedure to even better meet industrial requirements. Even, though only tested once, this indicates reasonable reliability for the age-differentiated assessment tool. However, no statistical testing of the procedure to derive the input data for the assessment tool, and also no repeated analysis has been conducted. Nevertheless, due to the procedures design discussed in the objectivity section reliability is generally assumed to be high.

8.1.1.4 Applicability and effort for analysis and evaluation.

An essential characteristic for the operational application is the applicability and the required effort for data collection, analysis and evaluation of the results. Due to its standardisation and formal structuring of the data collection, evaluation and interpretation, the procedure is designed to be easy to be used and time efficient. Users with only basic knowledge in workplace ergonomics are able to use to tool, based on the guided process in the EXCEL application. Due to the calculation of the results based on a few input parameters, the assessment, interpretation and documentation of results is immediately available upon data input. This was perceived as beneficial by industry representatives, as the calculation and discussion needed to derive average values for weight, postures and energy rations was the most time consuming part of the assessment. This issue was resolved by implementing the observation protocol and the combined assessment of multiple tasks, postures or weights in one assessment. However, as the new method provides a more holistic assessment regarding body postures and multiple task assessment, the observation of workplaces and gathering of required input data is more time consuming than before. Here, the suggested worker survey can shorten the time required by the assessor. Based on survey results, the most stressing tasks are known (time saving in identifying relevant tasks for assessments on site) and the evaluation can be timed so that the tasks can be observed (avoidance of the need for reassessment). Depending on the results of the worker survey, observation interviews and workplace evaluations conducted by the author of this thesis, the time required for answering the worker survey is about 10-15 minutes. Based on these results, a workplace observation can be conducted in about 15-30 minutes. Based on the evaluation protocol post processing for data can be conducted in another 15-30 minutes. This is comparable to times currently required for the evaluation of the workplace at the partner, using a non age-differentiated tool. However, in addition to current results, also body postures are evaluated and the share of estimated data is smaller with the new tool.

8.1.1.5 Acceptance of the process results

Acceptance of the results was high in terms of both, the practical requirements and the methodological approach. To evaluate the acceptance of results, a focus group with industrial experts was conducted, where the observation protocols and assessment results were discussed with an occupational physician, safety officers and worker's council representatives. The structured procedure, clear rules and the inclusion on objective information as well as worker information's in the assessment was perceived as beneficial and as an improvement compared to the assment results currently in use. Also the scaling of the risk value with age was perceived as a beneficial information for preventive workplace design or worker allocation. To evaluate results against worker perception, the result of one workplace evaluation was discussed in both companies on worker level. Even though this was conducted in a workshop setting with a low number of participants, the age independent evaluation was approved to fit the workers' perception of their workplaces. Futher, the age-differentiated assessment was perceived as a suitable measure for the work place as it qualitatively helped to explain differences in the perception of risk ratings between younger and older participants in the group. For 86% out of the 44 assessed categories the risk assessment was approved by younger and older workers. In the remaining 14% of the categories, the stress or risk was estimated to be the same, or even higher as suggested by the age-differentiated assessment for the age of 50 years. The categories perceived as more critical than evaluated included kneeling, work in bendt positions, and lifting. For the most part of the assessment the age-differentiated risk values fitted the workers' strain perceptions (seeTable 33 for results of the strain assessment)

Table 33: Strain assessment in different departments and related risk levels according to Table 4

Department	Work area	Number	Average age	Forced body posture	Bent posture	Squatting	Kneeling	Standing	Sitting	Walking	Holding	Carrying	Lifting	Push Pull	Over head	Heavy phys. work	Overall work strain
Logistics	Incoming goods and transport	7	37.6	9.8	10.5	9.8	6.8	11.7	6.1	7.6	8.5	10.0	12.1	7.7	6.7	9.1	12.3
	Order picking	10	38	11.9	13.6	10.7	9.6	11.9	9.1	8.3	13.2	12.6	14.8	9.3	10.5	14.4	14.0
	Packaging and shipping of goods	12	30.6	11.7	11.3	9.2	9.0	8.6	6.4	7.4	11.4	11.8	12.4	10.3	7.2	12.5	11.5
Service	Servicing customers	15	39.5	6.9	7.4	7.3	7.1	7.0	7.0	6.7	6.9	6.8	7.7	7.1	7.6	6.4	8.8
	Shelf management	30	38	6.6	9.7	8.2	8.6	6.9	6.0	6.8	8.5	9.6	11.5	7.4	6.6	6.0	12.8

8.1.1.6 Limits of process application

The developed method is considered suitable in operational practice as an age-differentiated screening method able to make predictions about possible age-critical workplaces and tasks based on standardised performance values of healthy persons. Thus, this method is intended to build awareness for different strain levels and for on average lower ability levels, by illustrating the average change in the risk level according to the strain focused approach. Since ageing is an individual process, the results are valid for an average person of the age under consideration. Thus, based on the aggregated results, no statement can be derived for the individual and for performance limited workers. Even though the procedure enables the manual input of a remaining capacity for the age-differentiated assessment on aggregated level (strength, endurance and physical capacity) this level of aggregated data is not suitable for individual assessments. By entering low levels of remaining physical capacity e.g. 5% for a worker, who is not supposed to lift heavy weights, the procedure provides an up scaled risk value for lifting tasks. This implies that at a risk rating of 10 points (green) for a lifting tasks is up-scaled to an individual risk value of 200 points (red), indicating the mismatch between ability and requirement. However, individual detailed assessments have to be conducted in case of specific requirements and the subjective strain perceived by a worker has to be considered as an individual reaction to the workload in an in-depth analysis. Further, limitations exist in relation to excluded stress types of action forces and repetitive manual work. They were not considered, as they were judged as not important in the specific context and cannot be evaluated with the tool. However, also for this type of stress, age-differentiated risk values might be suitable.

8.1.1.7 Conclusion of the evaluation of the age-differentiated assessment tool

The developed tool builds on existing approaches for age-differentiated work assessment (see section 7.2.2), but provides age-differentiated values based on a scientific base for manual material handling and body postures and not just a general upscaling by one or several risk levels as conducted in the few available current procedures. The tool therefore can be considered as a new category of ergonomic assessment, situated between individual ability based assessment and general estimated risk upscaling. As a result, the effort in individual ability assessment is greatly reduced, while at the same time the accuracy of results is increased in relation to existing tools. The developed approach hence meets the industry specific requirements (section 5.4) and was perceived as a useful source of information in regard to the comparing evaluation of younger and older employees The structured assessment procedure, clear rules and evaluation results were highly appreciated by industry participants. Based on the interpretation of the results, a clear identification of physically age-critical workplaces is possible in relation to overall stress (working energy turnover) and task specific stress and strain (body postures, load handling). Especially, the combined assessment of different loads and task types was perceived as a benefit of applying the tool. An additional benefit in comparison to available job-match procedures is the generalized future oriented evaluation approach which enables the preventive planning of work stress without collecting detailed ability data from employees. The generation of such ability data is effort intense and thus only conducted for minority fraction of already ability limited workers in industry, resulting in higher risks for other older workers, who are affected by general ability decline (cf. Wittemann 2017, p.114). The concrete, quantifiable results of the procedure, which can be used to derive a need for action and related field for improvement of workplaces, were particularly positively emphasised by practitioners. Overall the method proved to be effective for industrial needs and increased transparency for work place designers.

8.1.2 Discussion of the procedural quality of the improvement procedure

The process quality of the developed improvement procedure has been tested in two use cases and discussed with industry experts. Findings of this process are summarized below to discuss the process quality. As the two different case studies conducted in retail and manufacturing industry have revealed, the structured methodology is both, applicable and highly relevant for different industries. It meets the current requirements derived in the theoretical and practical investigation of this thesis, as summarized in chapter 5. The procedure clearly points out solutions for physical over stress and strain with a focus on person-oriented technical solutions as requested by industry. The participatory process implemented, also enables the avoidance of unsuitable solutions and strengthens worker acceptability and should, therefore, be beneficial for long-term use. Due to the selection of test cases in very different occupations from service to production it can be assumed that the selection procedure is generically applicable to most industries, independent from sector, involved tasks and work stress. The procedure is built upon a structured implementation methodology.

For the prototypical application of the improvement process, the process introduced in section 7.4 was carried out with both companies. Solutions for the problems identified in the empiric and assessment phase, were generated in a partizipatory design with workers in a workshop series with 3 workshops for each company (see chapter 4). The validity of the selection process is discussed for one workplace in logistics in one company. In this logistics department order picking was evaluated to be particular high in task related stress (standard 44.2, age-differentiated 52.1 point in the assessment – orange, and red category) while the energy expenditure assessment was at an acceptable level (4.556 kJ – yellow level). In the first workshop, several measures were created by the workers that participated. The analysis of the measures resulted in 43 measures of which 27 were of technical, 12 of organizational and 4 of human related nature. However, the assessment of the measures according to the age-differentiated evaluation procedure revealed that, due to the tasks specifications, automation is not viable and the use of stationary working aids such as cranes is not feasible. Further, organizational measures were evaluated as low regarding their impact on strain, and human related measures were classified as low reguarding assistance and utilization in the assessment matrix. The three measures with a rating in the high priority area in the priority matrix were all of technical nature and were identified as height adjustable workplaces and tables, hight adjustable scissor lift trucks, wearable sensors to improve work execution and indicate temporary overstrain, and exoskelettons for a better load distribution and a load reduction in the lower back. The last measure was perceived to be the most promising as most workers had some type of pain in this body region. Moreover, it was perceived as particularly useful in relation to elderly workers, of which a large fraction suffer from back pain. In summary, according to the workshop results, the most feasible assistance technology were exoskeletons for lifting and carrying activites, and the reduction of postural strain in the back. As a result, a suitable market available exoskeleton was rented for this purpose for industrial testing of its contribution to the reduction of preceived strain. The testing of the technology in the logistic department took place in november 2019 for three days. Overall 30 workers from the department tested the system (age: MW= 35.0, SD = 10.7, height: MW= 176.3 cm, SD = 7.7 cm, weight: MW= 82.4 kg, SD = 19.2 kg, WAI: MW= 40.7, SD = 5.4) for about 30 minutes.

All workers provided the information that they had no experience in using an exoskeleton. A test procedure as introduced in section 4.2.2 and section 7.5 was applied, managed by the author of this thesis. The PRE-condition test revealed that according to the current way of conducting the work, workers perceive an exertion of 14.8 points at the RPE scale for lifting tasks. According to the criteria in Table 4 this RPE rating is evaluted as a high workload and therefore categorized as red . As result of this high stress level, about 59 % of the participants provided the information that they were affected by back pain in the last six months, whereas the average severity of that pain was named to be 2.7 / 10 (SD = 2.0) points on the BORG CR 10 scale. Data analysis was carried out after the testing. The Shapiro-Wilk test revealed a gaussian distribution for the sample, after four clear outliers had been removed. The POST-condition test showed a significant reduction of perceived exertion in lifting tasks as an effect of applying the selected exoskeleton, as shown in Figure 74. It can be seen that the average reduction of the perceived strain is reduced by on average 3.97 points (SD = 2.77) in this condition ($t = 7.707$, $p < 0.001$, $n = 29$).

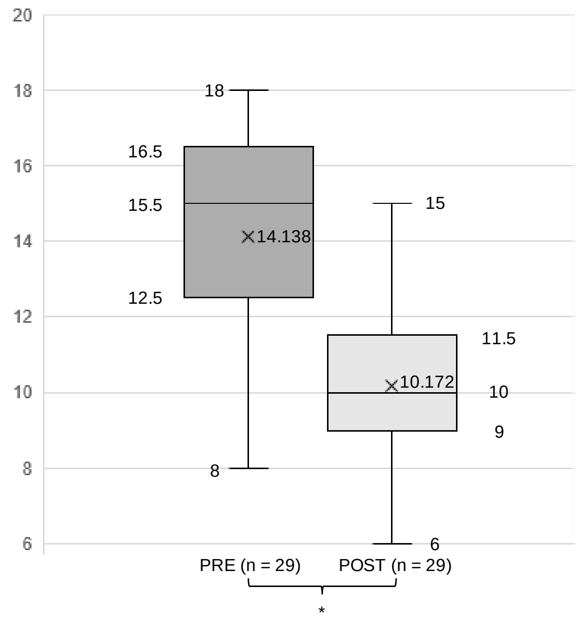


Figure 74: Boxplot for the dependent variable of RPE (dark grey) and POST condition. Significance is indicated with (*)

Moreover, the test result show multiple different impacts of the technology on work execution for the 14 tasks included in the assessment. Despite the limited sample size, given the underlying normal distribution of the lifting task, it is reasonable to assume similar results for the remaining tasks Figure 75 provides the results of the strain reduction achieved by using an exoskeleton to assist lifting and postural strain in the back for 32 workers in the logistic department. The results show the perceived difference in strain when conducting the work tasks with and without the system. The results are displayed over all workplaces assessed in the logistics department of one partner showing that the exoskeleton has different positive and negative effects on different work activities.

Figure 75: Testing results for exoskeleton type 3 at workplaces in logistics department (n=32) for 14 different tasks evaluated

It can be concluded from Figure 75 that the technology provides substantial support for postural strain and manual material handling, while especially sitting becomes more strain full with the technological aid. The average perceived strain reduction can now be used to re-evaluate workplaces after the intervention based on the perceived strain of the worker. Based on these test results, it can be concluded that both, the selection procedure and the technology evaluation procedure developed are, on the one hand, valid, and on the other hand, suitable for practise. Also the successful selection and testing process at the second company partner with similar technology showed resembling results. Thus, overall, it can be concluded that both processess are also objective and reliable in terms of their outcomes.

8.1.2.1 Acceptance of the process results

Based on the participatory development and selection of the intervention measures, the selected measure was accepted by the workers and a high voluntary participation in testing was achieved. Further, a high acceptance for the results derived by the evaluation procedure was found in both companies. The effects of applying the tested system in other work areas can be derived based on the average load reduction in the tests. These assumed effects in strain reduction on workplace level and the associated change of the strain-based workplace risk level for different types of work strain is illustrated in the comparison of the PRE and POST situation for using exoskeleton of type 3 transferred to the transport, order picking and goods receiving department in Table 34.

Table 34: Expectable results of using type 3 exoskeletons on strain in different departments showing the risk reduction based on perceived strain (green – low, yellow – middle, orange – high, red – very high risk)

	Forced body postures	Bent posture	Squatting posture	Kneeling posture	Standing	Sitting	Walking	Holding of loads	Carrying of loads	Lifting of loads	Pushing and Pulling	Static over-head work	Overall strain reduction
Transport													
As is	9.8	10.5	9.8	6.8	11.7	6.1	7.6	8.5	10.0	12.1	7.7	6.7	12.3
Type3	6.2	7.0	7.3	6.0	11.0	9.1	8.5	4.8	6.8	8.0	6.0	6.0	8.5
Order picking													
As is	11.9	13.6	10.7	9.6	11.9	9.1	8.3	13.2	12.6	14.8	9.3	10.5	14.0
Type3	8.3	10.1	8.2	7.3	11.1	12.1	9.2	9.5	9.4	10.7	6.6	7.1	10.2
Incoming and outgoing goods													
As is	11.7	11.3	9.2	9.0	8.6	6.4	7.4	11.4	11.8	12.4	10.3	7.2	11.5
Type3	8.1	7.8	6.7	6.6	7.9	9.4	8.3	7.7	8.6	8.3	7.6	6.0	7.7

Based on test results a decrease of the strain based risk level by one or two categories can be calculated based on Table 34. Tasks particularly effected positively by this system are working in forced body postures, working in bent body posture, holding, carrying and lifting and the overall perceived work strain at the workplace. However, also an increasing risk for standing and walking is to be expected as for these categories the perceived strain increased. These results were generally accepted by industry experts, however, more testing is needed to verify this transfer of results to other workplaces and workers, due to other requirements present at other workplaces and the small sample size in testing.

8.1.2.2 Applicability and effort for analysis and acceptance of the process results

In relation to the applicability and effort, for selection and testing process, matched industrial expectations and requirements. Due to their high degree of standardisation and formal structuring of the data collection, evaluation and interpretation, the tools and concepts developed were perceived as easy and time efficient in application for the workers. The new method provides a more structured derivation of suitable measures in relation to the identified problem. This part of the process was evaluated as highly applicable in both companies. However, the testing of measures, especially the post-processing and analysis of the data was perceived as too time consuming for industrial application by the company partners involved.

Acceptance of the results was high in terms of the methodological approach. To evaluate the acceptance of results they were discussed with industrial experts, what resulted in a high level of acceptance. In conclusion both processes match the requirements, are feasible for industrial use and highly accepted by practitioners.

8.1.2.3 Limits of process application

The main limit of the selection process can be seen in the final step of the improvement phase, the selection of a specific suitable measure. Here, still a high degree of understanding of the technology, the work processes and environment by the operator is necessary and this step requires crucial attention in practice. Different types of systems provide different benefits and disadvantages as can be shown on the example from exoskeletons and the conducted testing. Figure 76 shows the comparison of five different tested systems across different work places and stress profiles in both company partners. Overall 95 workers participated in testing using five different types of exoskeletons. Very different results have been obtained for the average strain reduction for different work activities and systems. However, based on this results, a more specific guidance for the selection of a suitable system in relation to the work stress available can be provided. Taking into account the changes in perceived work strain (reduction and increase) the most suitable exoskeleton can be chosen according to specific overstraining tasks and by considering workplace specifics for other types of work.

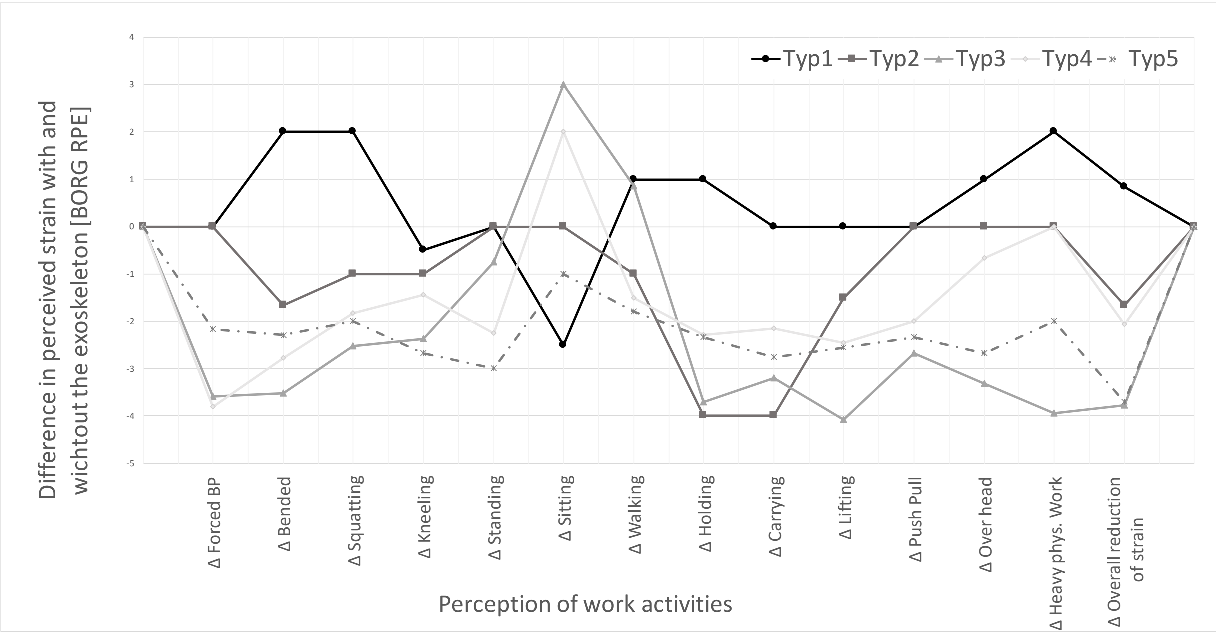


Figure 76: Strain reduction profiles for 5 different exoskeletons. Shown are the difference in perceived strain for different tasks for each exoskeleton as defined in the main text.

Table 35 shows the importance of the selection of a suitable type of exoskeleton in relation to the prevalent types of work stress and strain. Only by fitting the technology with the human and the work place a substantial and sustainable reduction of health risks can be achieved.

Table 35: Expectable results of introducing the different tested exoskeletons on strain in order picking on a RPE scale(green – low, yellow – middle, orange – high, red – very high risk)

Order picking	Forced body postures	Bent posture	Squatting posture	Kneeling posture	Standing	Sitting	Walking	Holding of loads	Carrying of loads	Lifting of loads	Pushing and Pulling	Static over-head work	Overall strain reduction
As is	11.9	13.6	10.7	9.6	11.9	9.1	8.3	13.2	12.6	14.8	9.3	10.5	14.0
Type1	11.9	15.6	12.7	9.1	11.9	6.6	9.3	14.2	12.6	14.8	9.3	11.5	14.8
Type2	11.9	11.9	9.7	8.6	11.9	9.1	7.3	9.2	8.6	13.3	9.3	10.5	12.3
Type3	8.3	10.1	8.2	7.3	11.1	12.1	9.2	9.5	9.4	10.7	6.6	7.1	10.2
Type4	8.1	10.8	8.9	8.2	9.6	11.1	6.8	10.9	10.4	12.3	7.3	9.8	11.9
Type5	9.7	11.3	8.7	7.0	8.9	8.1	6.5	10.8	9.8	12.2	6.9	7.8	10.3

The main limitation in relation to the assessment procedure is related to the subjective assessment of work strain by the workers. First, individual difference in the perception of the technology as well as in their acceptance might influence the test results. This can be counteracted by collecting such confounding variables. Second, a source of possible bias derives from the test procedure. Workers rate the perceived exertion not during conducting a work tasks, as intended in the original test, but after which might lead to a different rating as originally intended. However, for evaluating the perceived difference in exertion, as aimed for with the assessment, both test should show the same deviation, as both evaluations are carried out directly after the test experience. Third, a possible limit of the assessment is the ability of workers to objectively rate their perceived exertion and the differentiation of stress and strain types for evaluation. This miss-ratings can be prevented by explaining the questionnaire properly and by assisting workers that face challenges conducting the evaluation. Biases that occurred during the evaluation phase might show up as outliers, for which an appropriate treatment has to be devised.

8.2 OVERALL RESEARCH APPROACH AND IMPLICATIONS FOR THE PROCEDURE MODEL

Case studies conducted in the field are subject to the same requirements of good research as rationalist studies (Meredith, 1998, pp. 452–453). Relevant criteria for exploratory case study research are: the justification of the research approach, construct validity, external validity, and reliability (Yin, 2018, p. 87), which are discussed in this section.

The research approach was based on sampling considerations with the goal to extend the existing theory (Eisenhardt, 1989, p. 537). The cases selected for this study complement each other. While both cases had comparable requirements in the logistics departments, the specific requirements within the other departments studied provide insights in the other phases of the industrial value creation process and related types of work stress. On the one hand, the case in the retail sectordemonstrated the successful application of the model for service related occupations, as placing lightweight products into different storages, servicing customers with goods or working at cash desks. In summary, all these types of tasks include low loads and are dominated by stress from static to dynamic postural work. On the other hand, the case in the manufacturing of heavy machinery included stress based on repetitive work in line assembly, heavy physical work with large products, parts and tools, and a high amount of heavy manual material handling activities. Thus, overall, all types of work tasks in the continuum of physical work (see section 2.2.5) were included in the case study. The research process according to Ulrich was appropriate to derive short-term industrial benefits and scientifically grounded research results. According to this process all steps have been conducted successfully in cooperation with the industrial partners.

The relation of age, workability and physical assistance was examined in the field based on a research framework grounded in theory. Further, the concepts developed equally build on qualitative and quantitative data from the field study and literature. Construct validity was thus considered by the use of data triangulation of different sources of data and a clear chain of evidence in data gathering strategies as introduced in chapter 4 (Creswell and Creswell, 2018, pp. 199–201; Yin, 2018, p. 196; p.206). Moreover, construct validity has been ensured by reviewing and discussing preliminary results of applying the developed concepts and tool with industry experts, thereby iteratively improving the concepts during the course of the project (Yin, 2018, p. 87; p.327).

Internal validity was ensured by applying the developed research framework in data generation and analysis (Miles *et al.*, 2014, pp. 312–314). External validity was addressed by the two types of companies selected and the sampling of different workplaces and types of work stress in cooperation with the industrial partners (Miles *et al.*, 2014, p. 34).

Reliability was promoted in this study by clearly explaining the research approach, process, conducted steps and tools used. Further, this was addressed in using research protocols for all conducted data gathering (Yin, 2018, p. 180) the interviews, field observations and the setup of a database containing all related data (transcripts, field note, assessment results, audio-visual recordings of interviews and workshops, data from conducted testing, etc. (Yin, 2018, pp. 201–204; Eisenhardt, 1989, p. 537).

Finally, a proof of concept has been introduced in the industrial application of the age-differentiated assessment tool, the measure selection process based on this assessment and the evaluation procedure for the selected systems. Based on the proof of concept of the single steps of the procedure model, in combination with the consideration of requirements for good qualitative research, in its derivation, a satisfying contributions for both, industry and research can be concluded.

9 SUMMARY

The aim of this thesis was to derive a structured procedure for the identification of age-critical work stress and its adaption to physical assistance systems. In this final chapter, a research summary is conducted. The first section concludes on the relevance of the topic and summarized findings from the research process. Afterwards the quality of the research is discussed in comparison to existing knowledge. In conclusion the contribution to literature and findings for practice are highlighted. The thesis ends with an outlook where need for further research is outlined.

9.1 RELEVANCE OF THE TOPIC

Chapter 1 addressed the current demographic development. Different effects of ageing on health workability and consequences for employment in industrial companies were outlined and developments with regard to future production and resulting requirements for workers were summarized. Physical assisting systems were identified as promising solution for age-appropriate workplace design. Subsequently, the concrete objectives of the work were outlined and the structure of the work was presented.

9.2 IDENTIFIED CHALLENGES

Chapter 2 elaborated the relevant literature and thus builds the foundation for the generation for the development of the structured procedure. Therefore, a connection between physical workloads and potential health risks is established. Musculoskeletal disorders (MSD) as collective term for long term health risks were identified to be a particular problem for the ageing worker. Their relation to physical overload was analysed and in conclusion it was found that a high risk to develop MSDs particularly exist in relation to high work strain. High work strain was identified to result out of a mismatch between high physical work demands and low physical worker abilities. Subsequently, in the next section industry relevant physical abilities were derived. The second influence, namely the effect of age on these abilities was consequently expanded. In relation to physical worker abilities, age was found to be related mediator that leads to a significant average decrease of this prerequisites for healthy physical work. Thus, in the next section average effects of age on physical abilities were identified. It has been shown that especially all physical abilities on average decrease, despite of healthy living and training effect. The first section of this chapter closes with a conclusion of challenges for elderly workers at industrial workplaces in relation to declining physical abilities.

The second section of chapter 2 describes the ergonomic design process, as the control element of stress and strain at industrial workplaces. This process is divided in the two phases of the ergonomic assessment process, identifying health risks and designing the ergonomic intervention process, aimed at improving current conditions. Therefore, important basic knowledge of both phases were summarized. For the ergonomic assessment process, it was found that there are several different tools and methods currently available, that are mostly geared towards the evaluation of one type of stress under specific conditions. The results of these ergonomic risk assessments build the basis for the conduction of suitable ergonomic interventions. The analysis of current existing intervention clusters identified from literature showed that mostly stress reducing measures are at the focus and it was also identified that there is a missing connection for the transfer of risk assessment results to the intervention process. Besides general solutions for work stress reduction, measures summarized as secondary intervention exist that are targeted specifically towards strain control. Within this group physical assistance systems, as a newer approach, are seen as a promising solution for age-appropriate workplace design. Nevertheless, for the application of such technologies standard procedures and processes for their implementation and evaluation are missing. In the concluding analysis regarding industrial measures in relation to an ageing workforce the high potential of such measures for strain reduction is confirmed.

In the discussion of the basic literature both topicswere combined, deriving the requirement for research in the intersection of both topics. Key statements on the research gaps were drawn and the related need for research was highlighted.

9.3 RESEARCH APPROACH AND INDUSTRY SPECIFIC REQUIREMENTS

In chapter 3, the aims and objectives of the thesis are formulated based on the scientific need for research. The research questions were formulated and sub questions were derived.

Chapter 4 provided insights in methodological considerations made to derive answers for the formulated research questions.

Chapter 5 was aimed to clarify the industrial perspective on the topic and to derive related requirements for the procedure. The results of the field study showed that elderly workers are perceived as an asset by the companies studied and should therefore be protected from health impairments. However, at the same time, elderly workers showed the longest duration for sick leave and can be considered as a group at high risk. It was confirmed that high physical stress is particularly risk for elderly workers and most industry specific problems for older employees were identified to be related to or a direct consequence of overall workload, heavy lifting, and working in strenuous postures. Both companies stated the need for action in work design in relation to the demographic developments. and noted the missing consideration of older workers' ability profiles in workplace assessment, and the improvement process. Physical stress in relation to material handling, postural work and environmental conditions were considered to be most relevant in combination with an ageing workforce. Thus, this types of stress have to be included in an age-differentiated assessment. However, no current efforts in age-differentiated work assessment or design were identified in the field study. The conducted in depth analysis by means of a worker survey and the assessment of data provided by the company deepened this understanding of the as-is situation and confirmed aforementioned statements. In the worker a holistic picture of relevant tasks, to consider in the ergonomic assessment, was derived. Synthesizing the findings of the different empirical finding a requirement catalogue for the procedure was developed. It became clear that no current procedure or tool meets the company specific requirements.

9.4 THESIS RESULTS

Chapter 6 outlined theory about the model conception. The main parts of the process are introduced as define, evaluate, prioritize, improve, and verify and control. The procedure model developed is outlined as answer to research question three dealing with a structured approach for industrial practise.

Chapter 7 provided detail information about the conception of the different steps of the procedure. Phase one deals with the definition of the framing parameters of the project. In the second step, the ergonomic assessment methodology and the tool developed for age-differentiated workplace assessment was introduced and explained. This methodology was developed based on state of the art assessment tools and extended by an age-related assessment of risk, tailored to industrial needs derived in chapter 5. Thus the methodology provides the answered to research question one and the related sub questions. The third step of the procedure deals with the identification of the need for action the derivation of related fields for action, and the identification of suitable solutions. As a result, the developed ergonomic intervention framework is introducing a measure to provide the missing structure to the ergonomic intervention process. This methodology developed supports the targeted identification of suitable solution in relation the ergonomic assessment results. As a sub part of this section, research question two is answered. Based on literature, a solution catalogue that contains physical assistance systems was derived and evaluation criteria for the evaluation of a suitable application of such systems were defined. Based on the general assistance potentials of such solutions, an evaluation process for physical assistance was developed that supports industrial decision making on suitable solutions in relation for the field of action identified in the ergonomic intervention framework. This process thus answers research question 2 by identifying suitable solutions according to the age critical assessment of workplaces. The final step of the procedure introduced a structured process for the implementation and evaluation of the chosen ergonomic intervention. As no ergonomic assessment method for the evaluation of workplaces with physical assistance systems exists in literature, a new methodology to evaluate these systems in use was developed.

The research question formulated in chapter 3 were answered by the age-differentiated assessment methodology (RQ1), the structured solution catalogue of physical assistance systems and the related selection process (RQ2), and the procedure model for a structured identification and reduction of age-critical work strain (RQ3), as illustrated in Figure 77.

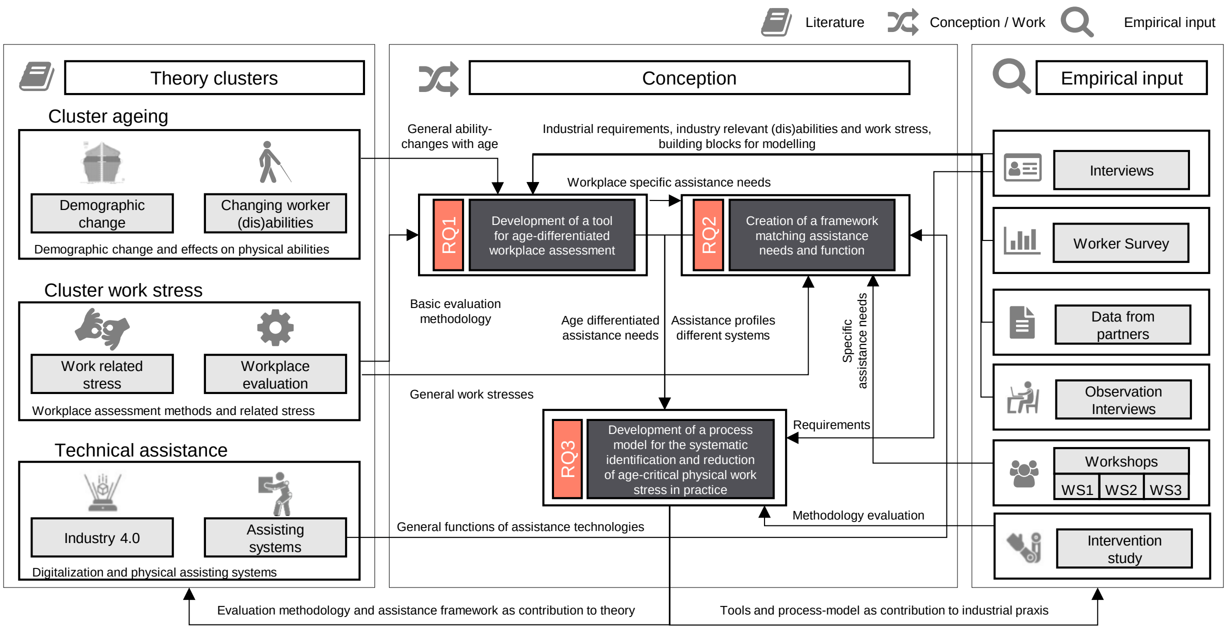


Figure 77: Research questioned, associated theoretical input and methods used. Bottom arrows show the contribution for industry and science

A strong focus was put on incorporating empirical finding from different sources and industry specific requirements to tailor the developed process to industrial needs, as aimed for in application oriented research. Figure 77 shows an overview of theory, model conception and related methods and information flow. It can be seen that the output of the developed model contributes to industrial practice (assessment tool, process model, improved work places) and scientific knowledge (assessment methodology, empirical findings about work related stress and strain and health outcomes and assistance framework). The contributions and limitations of the conducted work are summarzied in the next section.

9.4.1 Contributions and limitations

In this section the archived contributions for literature and practice are outlined, summarising the contribution of the conducted work.

9.4.1.1 Contributions to literature

The scientific literature was first expanded by industry specific age-critical work tasks and empirical insights from companies of the field of heavy machine production and retail, an aspect that had been neglected so far in literature. Second, the methodology for age-differentiated assessment of work tasks is a new approach combining ergonomic assessment methods for individual assessment with approaches for the consideration of age-related factors. However, this approach is not relying on time consuming individual ability assessment of individual workers and thus facilitates efficient preventive considerations and planning. At the same time, the approach is not limited to the derivation of age-differentiated load limits, nor to a general increase in risk level at a certain age but combines both, based on solid mathematical formulations of average ability declines and their consideration in ergonomic risk assessment. The developed methodology can be considered as unique and new approach holistic in scientific literature. Third, the developed ergonomic intervention framework extends the rare scientific literature for the ergonomic intervention process and summarizes and classifies existing ergonomic solutions for stress reduction and strain control. In combination with the developed procedure to rank ergonomic assessment results according to stress and strain based results into the matrix, the identified scientific gap between the ergonomic assessment and intervention process is tackled. Last, the holistic consideration and evaluation of physical existing systems in relation to age critical work stress expands the literature in this field.

9.4.1.2 Practical and managerial implications

In addition to contribution to scientific literature the discussion of the methodology and developed tools with practitioners has revealed several benefits as outlined here.

Raised awareness

The first main contribution for practise is seen in the objective presentation of existing issues in relation to an ageing workforce by the age-differentiated workplace assessment methodology and tool (section 7.2.2). Based on the inclusion of several objective data sources as sick leave days, exit interviews, injury statistics, age structure statistics, etc. and its statistical analysis, important KPIs can be derived for management. Based on these numbers, a raised awareness for the existing issues can be developed. While one company partner stated in the initial interview phase that there are no existing issues with elderly workers known by management at that time, several challenges related to age induced ability decline were identified during the course of the project. Based on subjective data, such as worker opinions on stressful tasks (worker survey), their perception of strain (Borg RPE for task and body region), and related improvements by the testing of exoskeletons strain reduction (comparison with and without) objective data can be derived and set in relation to the actual problems existing in operations. This helps to substantiate the objective findings and increases the acceptance of results, as well as awareness for existing problems of the workforce. While management provided the information that age-related issues play a subordinate role, also several problems in relation to physical complaints deriving from work were spotted based on the objective und subjective data presented. These issues were communicated to and accepted by management, thereby increasing the awareness for related problems. Based on both types of findings key challenges can be defined and their causes can be identified and improved based on the tools developed. This contributes to a better identification of age-related problems and the reduction of age-critical work stress and thus, for an overall improvement of the situation.

Increased focus on feasible solutions

A second main contribution is the ergonomic improvement framework and the structured process to identify possible focus areas (section 7.3.4). First, the holistic overview of possible measures and the guidance for their suitability based on workplace assessment results provides a standard and logical base for decision making and actions. Second, the structured comparison of measure benefits in relation to work place assessment results narrows down the types of suitable solutions to consider. Thus, a more structured and faster identification of meaningful solutions is possible. In addition, this enables the quick elimination of solutions which do not tackle the initial need for action and thus prevents the introduction of wrong measures. Moreover, the consideration of objective stress reduction in combination with the inclusion of subjective need for action and perceived usefulness of measures by workers enables a high acceptance and leads to high utilization later on. The method developed to evaluate effects of the intervention in relation to stress and strain is aimed at a profound scientifically grounded assessment of interventions' impacts and provides the possibility to transfer results to other areas by comparing need for assistance and the provided assistance by the technical system. Thus, by conducting the testing in one area, the feasibility of the measure can be determined for all departments and workplaces

Implementation support

Lastly, the procedure model developed is the overall main contribution to practice. The model provides practitioners with a step-by-step guide for identification of risks and possible solutions, their implementation and evaluation. Thus, it presents a sequence of recommendations that in combination enable the structured identification and reduction of age critical issues in practise. The main contributions within the model are the definition of involved roles, the methodology and industry-tailored tool for age-differentiated workplace assessment, the procedure for identifying the need and field for actions, the assistance system evaluation procedure and the evaluation methodology for such systems' benefits. A main benefit of the tool for system evaluation is the consideration of objective and subjective benefits of the solution in combination with economical aspects. The evaluation results show the benefit-cost related priority of a solution and thus this step can also be judged as beneficial from a tactical and strategic management perspective in terms of resource allocation.

Overall, the procedure met the industrial requirements and was evaluated as beneficial for industrial practice. However, some limitation in regard to the developments have to be highlighted. Firstly, the application of the procedure model does not replace specific case treatment of individual health limitations. The model was developed in accordance with industrial need for specific occupations and is thus not transferable without modification. The model is intended to provide a structured guideline of recommendations for occupational practitioners with a profound background knowledge in industrial engineering and ergonomics. Nevertheless, the critical reflection and interpretation of provided results by experts is necessary and the final decisions made are always the responsibility of the implementing industrial experts.

10 OUTLOOK

Although a large number of research findings on coping with demographic change is available in literature, it is still difficult to make concrete recommendations for age-differentiated work system design. Apart from macro level approaches, specific examples for industry and specific research results are currently lacking. As a result of current practice, more age-specific problem areas are prevalent in industry due to an increasing average workforce age, which require quantifiable ergonomic statements. The methodology developed in this thesis suggests a novel method to change the current reactive to a data-based preventive approach. Provided the scope of the topic and the small sample included, the results obtained can only be considered as a first step towards a better understanding of the future role of physical assisting technology in relation to the ongoing population ageing. It can be concluded based on the research need identified from literature and the initial results provided by this project that several interesting research opportunities within this topic were opened.

Main topics for further research include the human resource-oriented point of view, the workplace design-oriented approach and the technology domain. For the human centred field of research, further investigations should be conducted based on case study research to obtain deeper insights in the connections of age, health and workability in relation to physical work stress during the working life. Particularly dose-response quantifications requiring longitudinal approaches are necessary to derive better insights. In line with recent technological developments the rapid change towards digitalized production deserves critical attention in relation with the ageing workforce.

In relation to workplace design there is a lack of knowledge considering validated scientific models for age differentiated workplace assessments in industry. The concept introduced in this thesis can be seen as a crucial first step towards such models validated in a specific industrial setting. The approach of adapting ergonomic risk ratings based on strain assessments and general population data has to be scientifically validated in more detail. Alternative approaches should be developed and tested, in particular the evaluation of workplaces based on individual characteristics and strain deserves attention. More reliable mathematical models describing the increase in strain with age at constant workload in industry as recently provided by Börner are required (Börner, 2019, p. 95). With such results and updated psychophysical grading functions for the relation of stress and strain as first provided by Stevens and Galater for lifting (Stevens and Galanter, 1957, p. 389), a strain based ergonomic also ergonomic age-differentiated workplace assessment could be conducted without relying on individual ability measurements, or population specific ability forecasts. However, therefore, the stress strain correlation for industry specific tasks have to be derived by researchers. In relation to the design measures for workplaces more high quality intervention studies on the effects of measures in real life context have to be carried out to conclude reliable statement in relation to the group of elderly workers. Here research is needed considering suitable field study intervention studies that assess the results of different measures also including net technical solutions.

It can be concluded that the present study serves as one of the first systematic studies that assesses the benefits of physical assistance systems on strain reduction for the worker. Expanding on the procedure suggested here, more empirical data has to be collected in settings relevant for the industrial practice as as testing technologies in laboratory settings based on single muscle activity does only provide limited insight for field application. Clearly, a paradigm shift in the general research approach towards field application is needed.

Based on current results, new technologies such as exoskeletons can provide substantial physical support and strain relieve, making them highly relevant for the group of elderly workers. The findings presented in this thesis clearly indicate that these systems are the most promising candidate to promote a long and healthy work life. When data about their long-time effects on health become available it will be revealed if physical assistance systems as exoskeletons will be able to counteract the demographic challenges in industrial blue-collar work.

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12 APENDIX

12.1 INTERVIEW GUIDELINE MANAGEMENT AND EXPERT LEVEL

Interview guideline ENABLEME 50+

Level: Management (M) and Occupational medicine/health and safety expert (E)
Management (M): Executive management, board of directors, group personnel management
Expert (E): Occupational medicine/health and safety experts

Information about the interview partner

- Name. position, length of service and corporate history
- Education/preliminary training and work experience

Demographic change

1. M + E: Why do you deal specifically with the issue of the empowerment of "older workers"?
2. M: To what extent is the age development systematically surveyed and serves as a basis for decision making and internal measures?
3. M + E: How will the age structure in the company change?
   - What accompanying changes are associated with this?
   - How will this affect the company as a whole? (opportunities/risks/challenges)
   - What are indicators of this?
   - How will the company deal with these changes?
   - What is the basis for recording, measuring and forecasting?
   - To what extent are concrete data available or how can they be derived?
4. M + E: What has already changed? What action were taken? (coping strategies/projects on the topic)
5. M + E: What significance do older employees have for the company?
6. M: What are the implications for recruitment and personell planning?

Changes in the work system

7. M + E: How did/do work tasks and jobs change?
   - What are the drivers of change? What changes affect older workers in particular?
   - What are the consequences for the company and its employees?
   - How does the company meet these challenges? What is the role of HR Management?
8. M + E: To what extent do digitalisation and the associated use of technological innovations (use of assistance systems, software, CPPS) currently play a role?
   - Which one? Why are they used (expectations)?
   - What challenges do you see yourself confronted with?
   - How will digitisation change your business (branch)/work? What work is automated/what remains for people?
   - What happens to light duty work places
9. M: How has the level of demands of tasks in the productive sector changed overall (product/manufacturing complexity in comparison to the sector or industry)?
10. E: How would you describe the current level of demands of work tasks in the productive sector (difficulty and complexity of tasks and activities -ancillary activities vs. skilled work; qualification level; need to use cognitive and mental competences -problem-solving competence etc.)?
11. M +E: To what extent does the age of employees play a role in this context?

Industrial health and safety

12. M: Which departments in your company deal with occupational health and safety? (Prevention specialists: company doctor, safety specialist, psychologist; works council; human resources department; safety officers)?
    - What decision-making and advisory bodies on health issues are there in your company and what topics do they deal with in detail? How do workers get involved?

Page 1/3

13. E: Where are risks and problems in occupational health and safety and work design (sensitive areas)?
    - What are the main stressors/risks in the area? How is the risk managed?
    - What can be done preventively or what has already been implemented?
    - Which requirements and procedures must be considered?
    - Which key indicators are collected on the subject of work design, occupational health and safety and health?

14. E: How are stress and risks assessed in the company (physical/psychological)?
    - Which tools are used (e.g. risk analysis/questionnaires for evaluating mental stress)?
    - To what extent are older employee groups given special consideration?
    - Which activities cause more problems for older workers?
    - Which factors should be considered separately in an age-differentiated assessment?
    - Where do current ergonomic assessment procedures fall short of the requirements in order to be able to take the factor age into account in the assessment of work (age-based and preventive limit values)?
    - Which age-sensitive "limit values" are applied/used?

15. E: What results are available for older employee groups? (Connection of age with physical/psychological strains/accidents/etc.)?

Age-related changes

16. M + E: How do people change while ageing -physical/physical, sensory, cognitive/mental, psychological/social?
    - Where are major changes in relation to work?
    - What do you notice about your older colleagues/MA?
        - What problems are/can you (be) confronted with as an older employee?

17. M + E: How does overall performance change with age?
    - E: What abilities are relevant for the work in the company and how do they change
    - To what extent do you see a connection between age and other criteria (e.g. susceptibility to errors, occupational accidents, illness and absenteeism, knowledge and know-how, experience)

18. M + E: How are older employees perceived in the company (burden vs. resource)?

Age-appropriate work (design)

19. E: In your opinion, which age-related changes are particularly important for operational processes and the execution of activities in productive areas?

20. E: At which workplaces the requirements of older employees need to be addressed in particular and why?
    - In your view, where do higher/lower physical and psychological stress arise with advancing ages? To what is this attributable?
    - For which activities/jobs in the productive sector are older employees consequently better/worse/not at all suitable (knockout criteria)?
    - What need for action and support and what challenges do you see here and in general?

21. M + E: What requirements do you have for age-appropriate workplaces or age-appropriate work design:
    - What should age-appropriate workplaces look like in terms of working environment/work organisation/working time/working material/work content?
    - To what extent can this help to keep older employees in their jobs or in the company?

22. M + E: What measures, programmes and training are there specifically for older employees?
    - What are they aimed at? (Maintenance of performance, health promotion, increase of occupational safety) Which measures are planned? What inspired you to do something? (Trigger of project)
    - How you manage light duty work places in the company?
    - How do you see the potential of these measures[1] to encourage employees to remain in certain jobs?
    - What criteria do you see as influencing factors? What do you see critically/where do you see problems?

23. M + E: How are voluntary measures of occupational health and safety or occupational health management handled in a budgetary way?
    - What concrete measures were implemented (last year)?

Page 2/3

24. M: To what extent has the issue of older employees/ageing workers been reflected in management and corporate culture?
    - Where is there a need for improvement and why?
    - How do you see the support provided by internal instructions for action? (company agreements, service instructions, etc.) and commitments (written management principles, statements, charter, corporate principles, etc.)?

Qualification

25. M + E: How would you describe the current level of work requirements in your company (difficulty and complexity of tasks and activities, required level of qualification)
26. M: How important is the further qualification of employees in your area?
    - What measures need to be conducted (broader, more specific, compulsory training) and why?
27. M: How are abilities/skills/knowledge and potential of employees on operational workplaces assessed?
    - At what intervals/at what time does a review of this take place?
    - To what extent are changes in the area of workplaces/working equipment taken into account (e.g. in the case of a redesign of the workplace through reorganisation or the introduction of new technologies or even the purchase of new machinery)?
    - How are bottleneck qualifications determined?
    - To what extent are older employees taken into account (retraining; exclusion of training and further training measures)?

Holistic age-management

28. M + E: To what extent is there an (integrated) occupational health and safety management system in your company? And what about age-mangement?
29. M +E: What do you understand under the term “age-mangenemt system”?
    - What are the inhibiting and promoting factors of implementation in the company?
    - Why are no such systems in place in practice?

Conclusion

30. M + E: What would you like to give us as conclusion?
    - What is important to you that we have not yet addressed during the interview?

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[1] Potential measures: Individually adaptable workplaces, age-mixed teams, age-specific training and furthertraining, company health care to maintain performance, use as trainer/consultant, lower work demands (strengthlimits, working hours, tasks, etc.), self-determined work (tasks, procedures, time sharing, etc.) part-time offers,technical assistance systems and technical measures, healthy nutrition in the company (what does that mean?),back training, anti-stress training, sports offers, health days (what do they look like/contain?), integration ofhealth-conscious employee management in FCE training, health-oriented communication measures (intranet,employee newspaper, meetings)

Page 3/3

12.2 INTERVIEW GUIDELINE OPERATIONAL LEADER AND WORKER LEVEL

Interview guideline

Level: Operational leader (OL) and **Worker (W)**
Operational leader (OL): Operational managers and employees with management responsibility (shift supervisors, production managers, store or division managers, production planners)

Information about the interview partner

- Name. position, length of service and corporate history
- Education/preliminary training and work experience

Demographic change

1. OL: To what extent does the topic of "demographic change" affect you? What does it mean for your department?
2. OL: To what extent do you follow the age development in your department?
   - What has already changed? What will change?
3. OL: Relevance of older employees in your area?

Changes in the work system

4. OL + W: How did work tasks and jobs change?
   - What? What are consequences? What particularly affects older workers?
   - To what extent do technological innovations (use of assistance systems, software, CPPS) currently play a role?
5. OL: To what extent does the age of employees play a role in this context?
6. W: Change in work related to length of service (age)?
   - How did your tasks change over time? What has changed?
   - What has become harder/easier or more/less challenging and why?
   - What will your tasks look like in the future?
   - Which activities and conditions do you find stressful, which are a positive challenge? Why?

Industrial health and safety

7. OL +W: Where are risks and problems in occupational health and safety and work design (sensitive areas)?
   - What are the main stressors/risks in the area? How is the risk managed?
   - What can be done preventively or what has already been implemented?
   - Which requirements and procedures must be considered?
   - Which key indicators are collected on the subject of work design, occupational health and safety and health?
8. OL: How are stress and risks assessed in the company (physical/psychological)?
   - Which tools are used (e.g. risk analysis/questionnaires for evaluating mental stress)?
   - To what extent are older employee groups given special consideration?
   - Which activities cause more problems for older workers?
9. OL: What results are available for older employee groups? (Connection of age with physical/psychological strains/accidents/etc.)?

Age-related changes

10. OL + W: How do people change while ageing - physical/physical, sensory, cognitive/mental, psychological/social?
    - Where are major changes in relation to work?
    - How have you changed with age?
    - What do you notice about your older colleagues/workers?
    - What problems are/can you (be) confronted with as an older employee?
11. OL + W: How does overall performance change with age?
    - To what extent do you see a connection between age and other criteria (e.g. susceptibility to errors, occupational accidents, illness and absenteeism, knowledge and know-how, experience)
12. W: What prejudices are you/your older colleagues confronted with?

Page 1/2

Age-appropriate work (design)

13. OL: What age-related changes are affecting work execution in your area?
    - At which workplaces the needs of older employees need to be addressed in particular and why?
    - In your view, where do higher/lower physical and psychological stress arise with advancing ages? To what is this attributable?
    - For which activities/jobs in the productive sector are older employees consequently better/worse/not at all suitable (knockout criteria)?
    - What need for action and support and what challenges do you see here and in general?
14. OL: What should be considered from an operational point of view when designing age-appropriate workplaces?
    - Which measures for age-appropriate workplaces would be suitable in your area (work environment/organisation/time/means/contents)?
    - To what extent can this help to keep older employees in their jobs, or in the company?
15. W: What should an age-appropriate workplace look like from your perspective?
    - What would you improve/change in your workplace (organisation, environment, means and content)?
16. OL + W: What measures[1], programmes and training are there dedicated to older employees?
    - What are they aimed at? (Maintenance of performance, health promotion, increase of occupational safety) Which measures are planned?
    - What potentials do you see in these measures to encourage employees to remain in certain jobs?
    - Are there jobs with reduced stress in the company? What is the procedure for allocation to such a work place?
    - What are influencing factors for prolonged working in your area?
    - What do you see critically/where do you see problems?

Qualification

17. OL + W: How would you describe the current level of work requirements in your area (difficulty and complexity of tasks and activities, required level of qualification)
18. OL: How important is the further qualification of employees in your area?
    - What measures need to be conducted (broader, more specific, compulsory training) and why?
19. W: How important is participation in training for you and why?
20. OL: How are abilities/skills/knowledge and potential of employees on operational workplaces assessed?
    - How are bottleneck qualifications determined?
    - To what extent are older employees taken into account (retraining; exclusion of training and further training measures)?
21. W: What qualifications/knowledge is needed for your job?
    - Where is experience particularly necessary?
    - Which knowledge of older employees must be disseminated before they leave the job?
    - Are there any work activities that that become easyer or heavier over time, or do the requirements remain constant?

Conclusion

22. OL + W: What would you like to give us as conclusion?
    - What is important to you that we have not yet addressed during the interview?

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[1] Potential measures: Individually adaptable workplaces, age-mixed teams, age-specific training and furthertraining, company health care to maintain performance, use as trainer/consultant, lower work demands (strengthlimits, working hours, tasks, etc.), self-determined work (tasks, procedures, time sharing, etc.) part-time offers,technical assistance systems and technical measures, healthy nutrition in the company (what does that mean?), back training, anti-stress training, sports offers, health days (what do they look like/contain?), integration ofhealth-conscious employee management in FCE training, health-oriented communication measures (intranet,employee newspaper, meetings)

Page 2/2

12.3 WORKER SURVEY QUESTIONNAIRE

1. General information:

Description	Answer	Description	Answer
Current work area		Active at current workplace for how many years	
Current workplace		Current age in years	
Job rotation between which other workstations		Expected stay in the department [years]	

2. Describe the normal workflow at your workplace per working day:

Description of the main work processes or work activities in keywords (e.g. assembling various parts with screwdrivers, processing work orders on the computer, commissioning of goods, cashing, tightening 30 screw connections with a torque wrench, etc.)

No	Table 1: Work activities	Quantity	Time share ☐ % ☐ h
1	~~Tighten thirty screw connections with a torque wrench~~	~~30~~	~~1h~~
2			
3			
4			
5			
6			
7			
8			
9			
10			

Is there a tact or standard time for completing the work? If so, which?		☐ hours ☐ minutes
The time allowance at the workplace is:	Sufficient ☐ Short ☐ Too short ☐	
Similar task sequences are repeated in a time span of (e.g. cashing, starting a new product, etc.)	With the tact ☐ Hourly ☐ About 4 hours ☐ Daily ☐ Weekly ☐ Never ☐	

Transfer the work activity number from Table 1 with the following contents:

Forced postures: e.g. kneeling, squatting, twisted body	Are there any ergonomic improvements in place? Which?	Is the work place individually adjustable? Name how?	Are working aids used? (cranes, balancer, etc.) Name which.
~~1 squatting whole tasks~~			~~4 crane for manual material handling~~

Page 1/2

3. Describe which work activities are particularly stressful and why

What is physically particularly strenuous:

What is mentally particularly strenuous:

Which workplace and which work activities are the most stressful in the area

4. Age-related aspects of the workplace

Are there any special regulations, special assistance or special work activities especially for long-time/old employees in the area/at the workplace

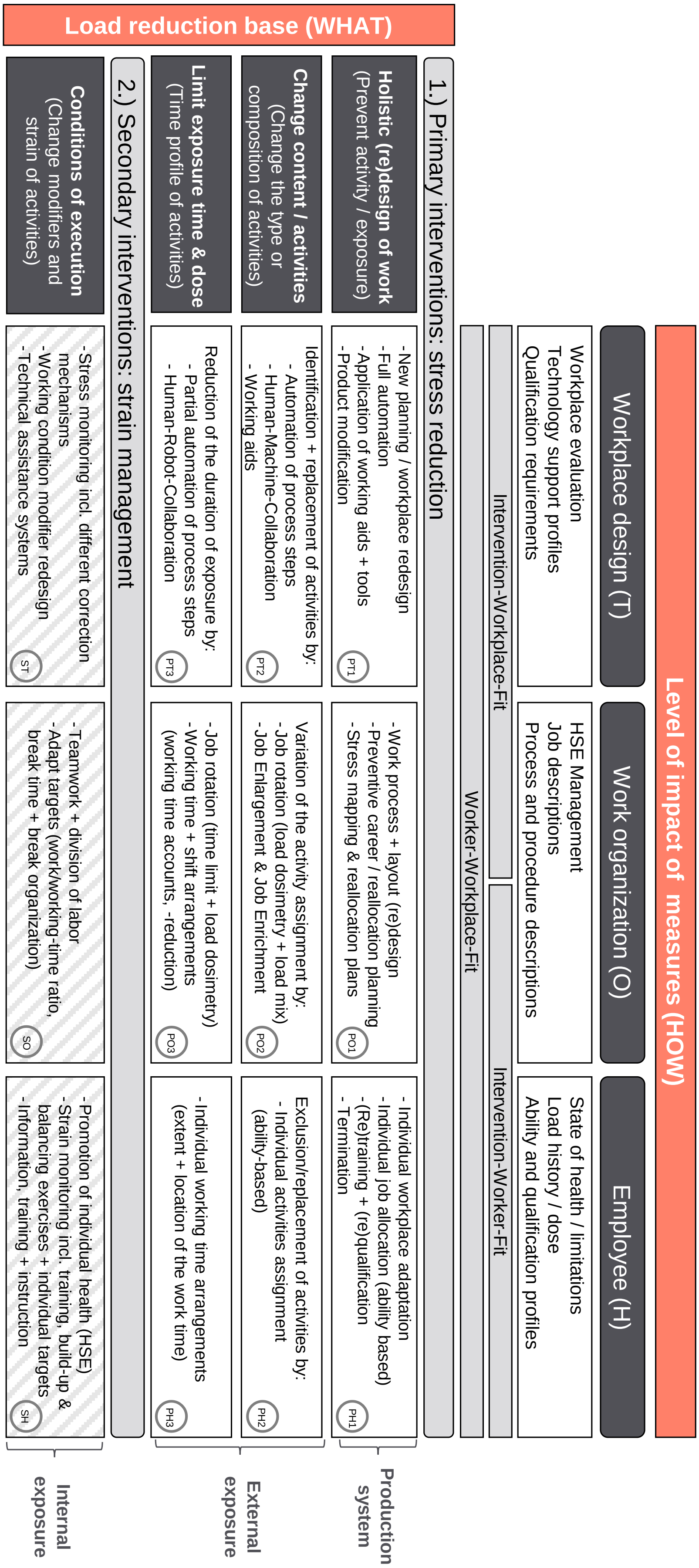
5. Overall assessment of the workplace

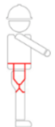
In this workplace the following is particularly positive:

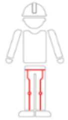
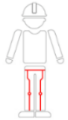
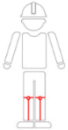
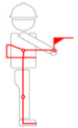
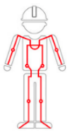
In this workplace, the following should be improved:

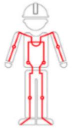
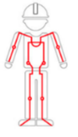
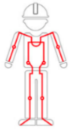
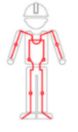
Page 2/2

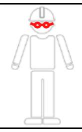
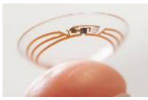
12.4 INTERVENTION FRAMEWORK

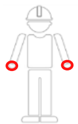


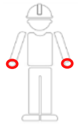
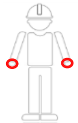
Type	Tech	Category	Description	Visualization	Example	Supported activities	Assistance performance	TRL	Price category	Example products	Source
Execution assistance	Physical support by exoskeletons	Exoskeleton shoulders and upper extremities	Supports workers working at or above shoulder height			BP: Overhead work and overhead assembly, mainly in line assembly	**Passive:** 30% less muscle fatigue during stretching and 20-30% reduction of muscular activity in the shoulder **Active:** Muscle activity reductions by 20–55% for shoulder muscles Decrease in muscular activity of 30-70% for the upper arms and shoulders in static holding	TRL 9	3	➢ Ottobock: Paexo shoulder* ➢ Frauenhofer: Exo Jacket ➢ SuitX: ShoulderX;* ➢ Ekso Bionics: EksoVest ➢ Comau: Mate* ➢ Levitate Airframe*	Hensel *et al*. 2018 Kim *et al*. 2018 Muramatsu and Kobayashi, 2014 Kobayashi and Nozaki, 2007 Alabdulkarim and Nussbaum, 2019
		Exoskeleton arms (elbows)	Supports workers in moving and bending their arms (rehabilitation)			LH: Lifting	Decrease in energy consumption (Not quantified) Increase strength (not quantified)	TRL 9	2	➢ Cyberdyne: HAL Single Joint ➢ Atoun: Model K* ➢ Exhauss Model A*	Kadota *et al.* 2009
		Exoskeleton Hand	Supports workers in gripping and holding objects			LH: Holding and carrying of tools	Increase in maximum compression forces and hand endurance (not quantified)	TRL 7	3	➢ Bioservo: Ironhand ➢ Daiya: Power Assist Glove	Radder *et al.* 2018
		Active Exoskeleton back	Supports workers under static and dynamic load in the area of the back muscles			BP: Bending LH: Heavy lifting	Reduction of muscle activity by 12–60% for back muscles and 30-75% in arms and shoulders in dynamic lifting Decrease in muscular activity of 70-80% for the upper arms and shoulders in static holding	TRL 7-9	3-4	➢ SuitX: BackX ➢ German Bionic: CrayX * ➢ Innophys: Muscle suit ➢ ATOUN: Model A*, AS*, Y*	Hensel *et al*. 2018, Bosch *et al*. 2016 Huysamen *et al.*, 2018 Kobayashi and Nozaki, 2007.
		Passive Exoskeleton back	Supports workers in static postural work and dynamic load handling in back muscles			BP: Bending LH: Lifting	Reduction of back muscle activity for lifting by 10-48% and on average 44% for static postural work Reduction lumbar moment by 20–30% Reduction of compression forces at the lower spine by 12-29%	TRL 9	2	Lifting ➢ PLAD ➢ Laevo: V2*	Hensel *et al*. 2018, Bosch *et al.* 2016 Abdoli-Eramaki *et al.*, 2007 Koopman *et al.*, 2019 Motmans *et al.* 2019
		Passive Exoskeleton back	Supports workers in static postural work and carrying of goods in back muscles			BP: Bending LH: Carrying	Enforcement of proper lifting techniques helps reduce the risk of back injury. Ergoskeleton design transfers much of the load of heavy lifting from the upper body to the legs. Helps reduce arm fatigue from lifting heavy objects	TRL 9	2	Carrying ➢ Strongarm: V22 ➢ Exomys: Atlas ➢ Exhauss Model W*, Model T*, and Model H*	Picchiotti *et al* 2019
		Exoskeleton back and hip	Supports the lower back of the worker for lifting			BP: Bending LH: Lifting	Reduces muscular activity in back muscles by about 14-20% but increase in leg muscle activity by about 10% in load handling	TRL 6-9	5	➢ Cyberdyne: HAL Lumbar Type* ➢ Active Link, Panasonic: AWN-03 ➢ ATOUN: Model Y*	Keehong *et al.* 2016 Glinski *et al.*, 2019 Miura *et al.*, 2018

Type	Tech	Category	Description	Visualization	Example	Supported activities	Assistance performance	TRL	Price category	➢ Example products	Source
Execution assistance	Physical support by exoskeletons	Exoskeleton legs (hip-knee ankle joint)	Supports the worker in lower limb area during stretching and bending movements of the legs			BP: Standing, squatting LH: Lifting, carrying	Average decrease of force by 40.5% when walking on a slope and 12.5% when climbing. EMG reductions of 20% to 36% in walking, climbing and descending reduced EMG and muscular effort of up to 32% for sit-stand transition and squatting Support for knee bending up to 60 kg of loading Increase strength (not quantified)	TRL 6-9	2-3	➢ SuitX: LegX ➢ Cyberdyne: HAL and single joint knee ➢ MINDWALKER ➢ ReWalkTM ➢ EXPOS ➢ Power assist wear ➢ Soft Exosuit ➢ RB3D: Hercule V3 ➢ TU Berlin: TUPLEE ➢ Yobotics: RoboKnee	Linner *et al.* 2018 Kim *et al.* 2013 Yan *et al.* 2015 Pratt *et al.* 2004
		Exoskeleton legs, knee and ankle	Supports the worker during long standing activities and during mixed stand-sit activities and squatting activities			BP: Standing and sitting	Relief of up to 70% of the body weight when standing For specific muscle groups 11-49% reduction of muscular activity.	TRL 9	2	➢ Noonee: Chairless Chair ➢ Honda: Bodyweight Support Assist ➢ Exomys: Daedalus ➢ SuitX: LegX	Hensel *et al.* 2018 Kim *et al.*, 2013 Hasegawa and Muramatsu, 2013 Luger *et al.*, 2019b
		Exoskeleton ankle	Supports workers when walking long distances			BP: Walking, climbing stairs	Reduces energy consumption during walking by about 7%	TRL 6-7	Not available	➢ Carnegie Mellon: ExoBoots	Collins *et al.* 2015
		Exoskeleton tool holder	Supports workers in holding and operating heavy tools while standing.			LH: Holding, manual work with heavy tools,	No general quantification of support available	TRL 9	5	➢ Lockheed Martin: FORTIS ➢ Ekso Bionics: ExoWork (currently not available)	Linner *et al.* 2018
		Exoskeleton for additional limbs (SRL)	An exoskeleton that provides the worker with additional robotic limbs. Relief of the whole body through systematic task sharing.			BP: Kneeling, squatting, standing, bending LH: Holding, carrying, lifting, pushing/pulling, repetitive manual work	No general quantification of support available	TRL 5-6	Not available	➢ MIT: SRL (prototype)	Parietti *et al.* 2014; Parietti *et al.* 2016
		Exoskeleton whole body	Supports the whole body at work			BP: Standing, kneeling, squatting, overhead work LH: Holding, carrying, lifting pushing/pulling	No general quantification of support available	TRL 2-6	4-5	➢ SuitX: MaX ➢ Sarcos: Guardian XO ➢ Panasonic, Activelink: Ninja	deLooze *et al.* 2016

Type	Tech	Category	Description	Visualization	Example	Supported activities	Assistance performance	TRL	Price category	Example products	Source
Execution assistance	Physical support by exoskeletons	Ergosuits or Ergo-skeletons	Lightweight elastic support for postural work and light material handling			BP: Bending, work in awkward postures LH: Light lifting	Reduction of back muscle activity by up to 17-24% in bending Reduction of perceived exertion in back muscles up to 67%	TRL 9	1	➢ SRI: Superflex ➢ Morita Holdings Corporation: Rakunie* ➢ Smart Support Technology: Smart suit* ➢ Paexo: Soft back * ➢ SSL*	Shimizu and Hanke, 2013 Hein *et al.*, 2016
		Powered Clothes	Actuators incorporated into clothing to support body movements.			BP: Walking, standing, awkward postures LH: light load support	No general quantification of support available	TRL 2-3	Not available	➢ Seismic: Powered Clothing ➢ SRI: Robotics Super Flex Exosuit	https://www.myseismic.com
		Working aids for moving and lifting of heavy loads.	Non-body worn manually controlled support systems. Relief of the worker during holding, carrying and lifting.			BP: Reduce bending LH: lifting, carrying, holding	Replacement of activity. Transfer of the load from worker to aid.	TRL: 9	1	➢ Hywema: UH Series ➢ Tiger: MKS-G series	Prasch 2010
		Intelligent arms for heavy tools	The holding arms hold the weight of the tool. They can be moved in all directions. Relieve the worker's arms and hold them home.			LH: Holding	Up to 16.3 kg weight of the tool is fully compensated. Holding load is reduced by 16.3 kg.	TRL: 9	3	➢ Ekso Bionics: Ekso ZeroG ➢ Lockheed Martin: Fortis Tool Arm	https://eksobionics.com/eksoworks/eksozerog/
		Customizable workbench	The customizable workbench can be adapted to different physical characteristics of the worker. Ergonomically unfavourable positions can be avoided			BP: Standing, sitting, lying, kneeing, squatting	Postural work stress can be reduced or avoided	TRL: 9	2	➢ Würth: Waps ➢ Zelenka: ZL Series	Neuhaus *et al.*, 2014 Pierce *et al.*, 2019
Execution assistance	Physical support to improve posture	Adjustable work piece holders	Adjustable workstations that place work pieces in a way that work can always be carried out in an ergonomically position (e.g. welding manipulators)			BP: Standing, sitting, lying, kneeing, squatting	Postural work stress can be reduced or avoided and lifting and holding can be conducted in a better body position	TRL: 9	2	➢ Adlatec welding manipulator ➢ Demmeler: Manipulator IP Robotix	http://www.siderosengineering.com/index/de/prodotti/show/3-achsen-schweiymanipulator
		Cobots	Relief of the worker during manual work, unfavourable postures and in lifting and gripping work pieces.			BP: Kneeling, bending, twisting, material provision	No general quantification of the support provided. Especially body postures improvements.	TRL: 9	5	➢ Kuka: LBR iiwa ➢ Universal Robots: UR10e	Fast-Berglund *et al.*, 2016 (Krüger *et al.*, 2009)

Type	Tech	Category	Description	Visuali-zation	Example	Supported activities	Assistance performance	TRL	Price category	Example products	Source
Perception assistance	Sensory support through optical and acoustic systems	Worker guiding systems	Systems for worker guidance by means of screens supporting the worker during multi-variant assembly by indicating the next work step to be performed.			Assembly	No general quantification of the support possible	TRL: 9	Variable depen-ding on design	➢ Crossbow: ELAM ➢ Assembly Solutions: AS Basic	Stockinger *et al.* 2019
		Smart Glasses or data glasses	Information is provided to the worker through augmented reality applications. The field of vision can be recorded and transmitted in real time to an expert.			Order picking, logistics, service, maintenance, assembly, production, training	No general quantification of the support possible	TRL: 9	5	➢ Google Glass; Sony: SmartEyelass ➢ Vuzix: M300 ➢ Ubimax: Glass Enterprise Edition	Makris *et al.*, 2016 Kasselmann *et al.* 2015
		Hololens	A virtual reality application that can display data in the field of vision, embedded in the environment			Order picking, logistics, service, maintenance, assembly, production, training	No general quantification of the support possible	TRL: 9	5	➢ Microsoft: Hololens 2	Evans *et al.* 2017
		Smart helmet	Helmets with a visor, which is a "Heads-Up Display" to show information's embedded in the environment.			Production, assembly, logistics, service, maintance	No general quantification of the support possible	TRL: 2	5	➢ Daqri: Smart Helmet	Apt, 2018; pp. 75
Perception assistance	Sensory support optical and acoustic systems	Smart lense	Required information is displayed in the worker's field of vision via an inserted contact lens.			Production, assembly, manufacturing	No general quantification of the support possible	TRL: 2	Not available	➢ Samsung: Smart Contact Lense (Under development)	Kasselmann *et al.* 2015
		Handheld devices	Information is displayed via wearable computers and interaction can take place via voice input, or a touchpad			Order picking, logistics, service, maintenance, assembly, production	No general quantification of the support possible	TRL: 9	2-3	➢ Panasonic: Toughpad FZ-E1 ➢ Honeywell: Dolphin CT60	Kasselmann *et al.* 2015
		Forearm computer	A forearm computer is a special form of a handheld that is fixed to the forearm with a holder. Information can be retrieved in the same way			Order picking, logistics, service, maintenance, assembly, production	No general quantification of the support possible	TRL: 9	2	➢ Zebra: WT 6000 ➢ Honeywell: Dolphin 70e /75e Wearable	Kasselmann *et al.* 2015

Type	Tech	Category	Description	Visuali-zation	Example	Supported activities	Assistance performance	TRL	Price category	Example products	Source
Perception assistance	Sensory support optical and acoustic systems	Smart watch	A smart watch, provides information directly on the wrist. The interaction is done via voice control or via the touch display. Most smart watches record body data of the wearer.			Order picking, logistics, service, maintenance, assembly, production	No general quantification of the support possible	TRL: 9	1-4	➢ Apple: iWatch ➢ ICS: 4Mobile Business Smartwatch	Morganti *et al.*, 2012 Kasselmann *et al.* 2015
		Projector wristband	A projector wristband displacs needed information directly as projection on the forearm. The handheld can also be operated directly on the projected surface			Order picking, logistics, service, maintenance, assembly, production, training	No general quantification of the support possible	TRL: 2	2	➢ Cicret: projector wristband	Apt 2018
		Projection-supported worker assistance system	Information is provided directly in the form of a projection on the workbench or work piece. This enables efficient work execution and error prevention			Assembly	No general quantification of the support possible	TRL: 9	5	➢ Assembly Solutions: AS Pro	Apt 2018
Perception assistance	Sensory support with haptic systems	Pick-by-light system	LED's guide the operator to next part to be used.			Order picking, assembly	No general quantification of the support possible	TRL: 9	5	➢ salt solutions ➢ Knapp AG	Theel 2015
		Pick-by-vision system	Smart glasses guide the operator to the location of the next part to be used or location.			Order picking, assembly	No general quantification of the support possible	TRL: 9	Variable depen-ding on design	➢ Google Glass; Sony: SmartEyelass ➢ Vuzix: M300 ➢ Ubimax: Glass Enterprise Edition ➢ Software: Knapp AG	Günther *et al.* 2009
		Pick-by-voice systems	Headphones are used to guide the operator e.g. location or appearance of the next part to be used.			Order picking, logistics, service, maintenance, assembly, production, training	No general quantification of the support possible	TRL: 9	5	➢ salt solutions ➢ Knapp AG	Kasselmann *et al.* 2015 Theel 2015
		RFID reader	RFID enables automated recording of activities and complete product traceability. Error prevention by providing real time signals.			Order picking, assembly	No general quantification of the support possible	TRL: 9	2-5	➢ Frauenhofer IFF: RFID Wristband ➢ Many more producers and applications for access systems	Kasselmann *et al.* 2015; Theel 2015

Type	Tech	Category	Description	Visuali-zation	Example	Supported activities	Assistance performance	TRL	Price category	Example products	Source
Perception assistance	Sensory support with haptic systems	RFID and Data glove	The glove detects movement and position of the hand and fingers relative to the environment, and the complete traceability of the products by immediately recording each removal.			Manufacturing, assembly, logistics, maintenance and service	No general quantification of the support possible	TRL: 9	2-4	➢ Virtual Motion Labs: VMG Series ➢ Immersion Corporation: (In development) ➢ Frauenhofer IFF: RFID glove	Kasselmann *et al.* 2015 Theel 2015
		NFC and smart Motion ring	A ring that is used as an NFC chip. Used for access restricted areas, for material tracking, payment transactions, detection of movement and position relative to the environment, etc.			Manufacturing, assembly, logistics, maintenance and service	No general quantification of the support possible	TRL: 9	1-2	➢ McLear: NFC Ring Lechal: Footwear ➢ Orphe: Smart Footwear ➢	Kasselmann *et al.* 2015
Physical support	Systems for ergonomics and health assessment	Ergonomics evaluation with sensors and simulations	With motion capturing, smart glasses, body attached sensors, cameras and ergonomics software a workplace is evaluated and potential for improvement is identified.			Manufacturing, assembly, logistics, maintenance and service	No general quantification of the support possible	TRL: 9	2	➢ Titanium Falcon Inc.: Talon Smarty Ring	Bullinger-Hoffmann and Mühlstedt, 2016 Guimaraes *et al.* 2018 Gudehus, 2008 http://www.linup.it/ergo/de/linup-system
		Smart clothes	Sensors incorporated into clothing collect and evaluate data such as pulse and muscle activity to detect e.g. fatigue or emergencies Virtual ergonomic evaluation based on the generated physical data			Manufacturing, assembly, logistics, maintenance and service	No general quantification of the support possible	TRL: 8-9	2-5	➢ AiQ: BioMan+ ➢ Xsens ➢ Linup: Ergo ➢ AiQ: Synertial	Singha *et al.*, 2019 Kasselmann *et al.* 2015
		Smart watch and activity Tracker	Environmental and body related data, is recorded and evaluated in terms of workplace stress and employee strain. Based on this data, preventive measures can be developed.			Manufacturing, assembly, logistics, maintenance and service	No general quantification of the support possible	TRL: 9	2-3	➢ Apple: Watch Series ➢ Fitbit: Fitness Tracker	Morganti *et al.*, 2012 Matusiewicz *et al.* 2018

12.6 TECHNOLOGY ASSESSMENT SHEET

Assessment sheet		Points				Solution 1
		Low (1)	Medium (2)	High (3)	Very High (4)	
Provided specific assistance						
1	**Objective task-related performance**	None or little assistance provided	Medium assistance provided	High assistance provided	Very high assistance provided	
2	**Subjective measure-workplace-fit**	System provides low benefits in relation to tasks and workplace	System provides medium benefits in relation to tasks and workplace	System provides high benefits in relation to tasks and workplace	System provides very high benefits in relation to tasks and workplace	
					Evaluation result A= sum (1-2)	
3	**User group**	One person	Small group of users	Medium group of user	Large group of users	
4	**Frequency of use**	Rare application for special tasks (< 10% of working time)	Average frequency of use (10-50%)	High frequency of use (50-80%)	Permanent application for all tasks (> 80%)	
5	**Fields of application**	Only for the special activity (<10% of tasks)	Some other possible activities (11-40%)	Several possible activities (41-70%)	Many possible activities (>70%)	
					Evaluation result B = sum (3-5)	
6	**Benefit of the solution (Result A x Result B)**	6-25 points	26-49 points	50-73 points	74-96 points	
7	**Transferability of solution to other areas**	The case is unique within the company	The case is transferable to a few other areas	The case is transferable to several areas	The system can be transferred to most other areas	
					Evaluation result C= sum (1-2)	
8	**Technology availability (procurement and transfer)**	Supplier and examples on the application in the specific context are available (TRL 9)	Supplier and examples on the application in other use cases (TRL 9)	Information on application of the technology in other use cases (TRL 8-9)	No information on application of the technology in use cases available (estimate effort based on TRL)	
9	**Internal use of resources (working time)**	Plug and Play purchase of a customized solution	Little need to adapt existing solutions to the company specifics	Need for bigger adaptation of the solutions to the company specifics	Creation of a new individual solution	
10	**Acquisition costs**	Low costs (<___ €)	Average costs (___ - ___ €)	High costs (___ - ___ €)	Very high costs (> ___ €)	
					Evaluation result D= sum (6-8)	
					Solution relevance = Result C / Result D	

12.7 PRE-QUESTIONNAIRE FOR SOLUTION TESTING

PRE Questionnaire

Dear participant,

within the project "EnableMe50+" we are investigating the effect of exoskeletons on employees.

The following questionnaire contains different statements. These relate to **your attitudes towards the technology, as well as your personal work situation including physical stress and your subjective feelings of discomfort and pain at work.** Please read each statement carefully. Then decide to what extent each statement applies to you and tick the appropriate box.

It depends exclusively on your personal assessment. There are no right or wrong answers or ratings. Trust your spontaneous judgement and do not leave out a single line!

The collected data will be used exclusively for scientific purposes. The evaluation is carried out anonymously and in compliance with the legal provisions of data protection (EU-DSGVO).

If you have accidentally ticked an answer that does not apply to you, please black out the circle completely and then tick the correct answer that applies to you.

Thank you very much for your participation!

Please enter your participant key first:

First letter of your last name (e.g. Max Mustermann)	
Mother's month of birth (two digits, e.g. **01** for January, **11** for November)	
First letter of the mother's first name (e.g. **M**aria Hofer)	
First number of your house number (e.g. Am Tor **2**5 or Mustergasse **9**)	

Page 1/5

Please enter the following personal data.

ENABLEME 50+

Personal characteristics	Answer		
Gender	○ Male	○ Female	○ Divers
Mother tongue			
Age in years			
Body height in cm			
Current weight in kg			
Smoking (number of cigarettes per day)			
Sport (duration per week in hours)			
Are you free of physical discomfort (no pain) today?	○ Yes	○ No	
Has there been a change of job for health reasons so far?	○ Yes	○ No	
Do you work part time (TZ) or full time (VZ)?	○ part time	○ full time	
How long have you been working for your current employer? (in years)			
How long have you worked in total in the area in which you are currently employed? (in years)			
Which workplace do you work at?			
What is your profession (exact name)?			

Do you have experience with exoskeletons?	○ None	○ Few	○ Medium	○ Much	○ Very much

Page 2/5

ENABLEME 50+

Please answer the following questions about your personal work situation (Work ability Index)

Nr	Question	Possible answers										
20	If you rate your best work ability ever achieved with 10 points, how many points would you give for your current work ability?	0	1	2	3	4	5	6	7	8	9	10

Nr	Question					
21	How do you assess your current ability to work in relation to the physical demands of the job?	Very bad	Rather bad	Average	Rather good	Very good
22	How do you assess your current ability to work in relation to the mental work demands?	Very bad	Rather bad	Average	Rather good	Very good

Nr	Question	Own diagnosis	Doctor's diagnosis
23	Tick your illnesses or injuries in the following list. Please also indicate whether a doctor has diagnosed or treated these diseases.	Own diagnosis	Doctor's diagnosis
	Accidental injuries (e.g. of the back, limbs, burns)	○	○
	Diseases of the musculoskeletal system of the back, limbs or other parts of the body (e.g. repeated pain in joints or muscles, sciatica, rheumatism, spinal disorders)	○	○
	cardiovascular diseases (e.g. high blood pressure, heart disease, heart attack)	○	○
	Respiratory diseases (e.g. repeated respiratory infections, chronic bronchitis, bronchial asthma)	○	○
	Psychological impairments (e.g. depression, anxiety, chronic insomnia, psychovegetative exhaustion syndrome)	○	○
	Neurological and sensory diseases (e.g. tinnitus, hearing impairment, eye diseases, migraine, epilepsy)	○	○
	Diseases of the digestive system (e.g. gall bladder, liver, pancreas, intestine)	○	○
	Diseases in the urogenital tract (e.g. urinary tract infections, gynaecological diseases)	○	○
	skin diseases (e.g. allergic rash, eczema)	○	○
	Tumours / Cancer	○	○
	Hormone / metabolic diseases (e.g. diabetes, obesity, thyroid problems)	○	○
	Diseases of the blood (e.g. anaemia)	○	○
	Congenital ailments / diseases	○	○
	Other ailments or diseases: Which ones? ____________________________________ (please fill in	○	○

Nr	Question	
24	Is an illness or injury currently hindering you at work? If necessary, please tick more than one answer option.	
	No illness / no impairment	○
	I can do my job, but I have complaints.	○
	I am sometimes forced to work more slowly or change my working methods.	○
	I am often forced to work more slowly or change my working methods.	○
	Because of my illness I am only able to work part-time.	○
	In my opinion, I am completely unable to work.	○

Page 3/5

ENABLEME 50+

25	How many full days have you been absent from work due to a health problem (illness, accident) in the last 12 months?	None	Less than 9 days	10-24 days	25-99 days	100-365 days
26	Based on your current state of health, do you think you will be able to continue your current job for the next two years?	Unlikely		Not safe		Pretty sure
27	Have you recently completed your daily tasks with pleasure?	Frequently	Rather often	Sometimes	Rather rare	Never
28	Have you been busy and active lately?	Always	Rather often	Sometimes	Rather rare	Never
29	Have you been confident about the future lately?	Permanently	Rather often	Sometimes	Rather rare	Never

Please answer the following questions about the physical effects of your work (based on Nordic questionnaire)

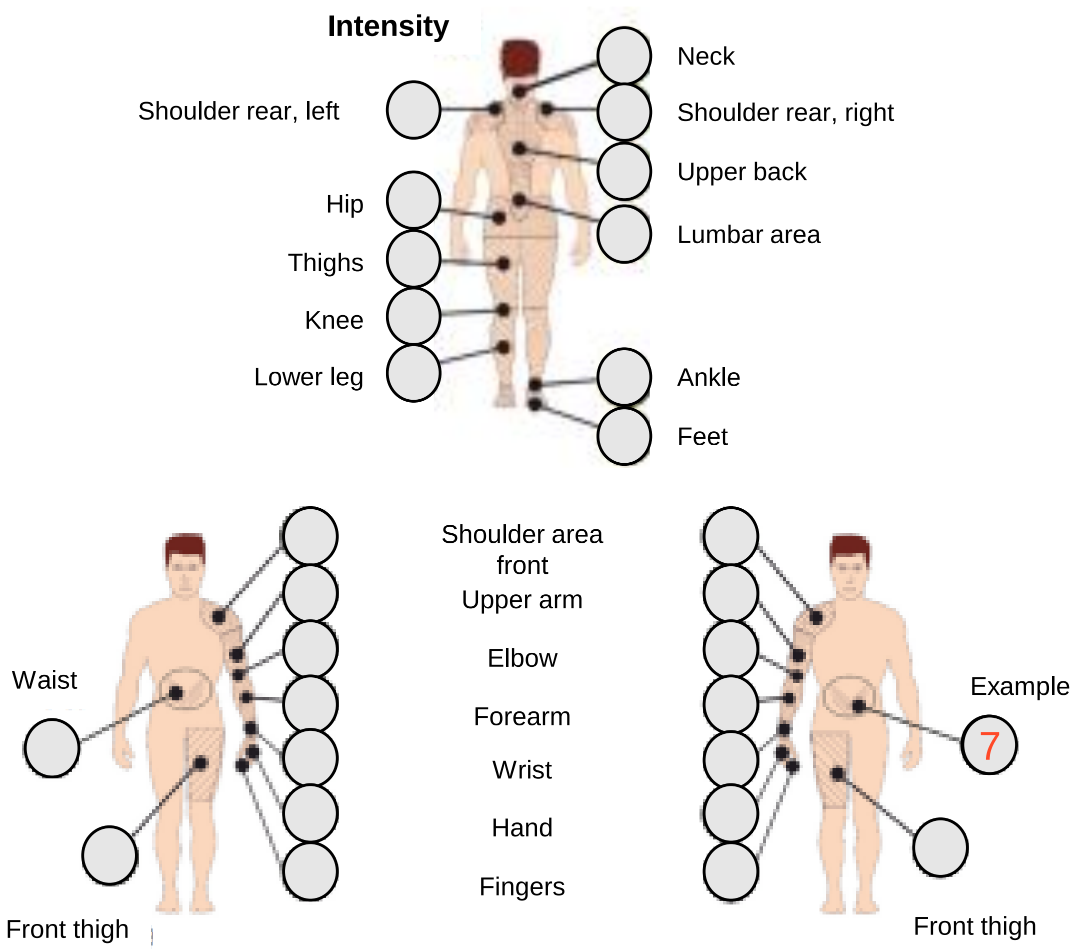
Nr	Question	Answers				
31	Do you currently have or have you had physical complaints within the past year?	Yes			No	
32	What complaints would you classify as consequences of your work activity?					
33	Have you been under medical treatment for the last 6 months because of the above mentioned complaints?	Yes			No	
34	How often do these complaints occur?	Ongoing		Occasionally in different activities		Occasionally in certain activities, namely ______________
35	When will the symptoms subside?	Not at all	After a vacation	After the weekend	After one night	After a break
36	Do you feel restricted by the discomfort of your work?	No		Low		Substantial

Subjective perception of complaints and pain at work (own compilation based on BORG CR10 scale and body map from (Groos *et al.*, 2020, p. 78)

Indicate the parts of your body where you feel discomfort and/or pain on/after a normal working day. For local classification, a body map is used to indicate the respective body regions. The scale given in the table serves to determine the intensity of the complaints. At the left end of the scale, "0, noting at all" means no complaints or pain. The right part of the scale, "10, extremely strong", means the greatest complaints or pain you have ever experienced or can imagine experiencing. Please look at the scale to see the different levels you can choose from

Nothing at all	–	Extremely weak (just	–	Very weak	–	Weak (light)	–	Moderate	–	Strong (heavy)	–	Very strong	–	–	Extremely strong (almost		Maximal
0	0,3	0,5	0,7	1	1,5	2	2,5	3	4	5	6	7	8	9	10		

When we ask you to evaluate the intensity of your discomfort and pain, try to assess your feeling as honestly as possible. Do not underestimate or overestimate it. Some people are a bit too insensitive or want to be "courageous" and judge complaints as too low. Try to state the complaints as you perceive them. We are only interested in your own subjective assessment. Look at the terms and give an assessment for each circle. You can also use intermediate values or a value greater than 10 if necessary. If you do not feel any discomfort, you can also leave the relevant fields blank.



12.8 POST-QUESTIONNAIRE FOR SOLUTION TESTING

POST Questionnaire

Dear participant,

within the project "EnableMe50+" we are investigating the effect of exoskeletons on employees.

The following questionnaire contains different statements. These relate to the **technology you have just dealt with, your attitudes to technology in general, and the workload reduction that can be achieved through technology.** Please read each statement carefully. Then decide to what extent each statement applies to you and tick the appropriate box. It depends exclusively on your personal assessment. There are no right or wrong answers or ratings. Trust your spontaneous judgement and do not leave out a single line!

The collected data will be used exclusively for scientific purposes. The evaluation is carried out anonymously and in compliance with the legal provisions of data protection (EU-DSGVO).

If you have accidentally ticked an answer that does not apply to you, please black out the circle completely and then tick the correct answer that applies to you.

Please enter your participant key first:

First letter of your last name (e.g. Max **M**ustermann)	
Mother's month of birth (two digits, e.g. **01** for January, **11** for November)	
First letter of the mother's first name (e.g. **M**aria Hofer)	
First number of your house number (e.g. Am Tor **2**5 or Mustergasse **9**)	

Please answer the following questions about the use of the exoskeletons (own compilation)

Nr	Question	Answers				
1	Which exoskeleton did you use?					
		Daedalus	Atlas	Laevo 2.5	Rakunie - Softexoskelett	Paexo Soft Back
2	How often did you use the system filed?					
3	How long did you wear the system? (in minutes)					
4	How much relief do you feel from the exoskeleton?	Barely 0-20%	Little 21-40%	Medium 41-60%	Strong 61-80%	Very strong 81-100%
	Did the exoskeleton force you to change the way you do your work?	Hardly	Little	Resources	Strong	Very strong
6	The time needed to carry out the work has been reduced by the system:	Highly increased (longer duration)	Slightly elevated	Not modified	Slightly reduced	Greatly reduced (shorter duration)
7	How do you rate the wearing comfort of the exoskeleton?	Very low	Low	Resources	High	Very high

Page 1/3

Physical stress and support from the technology in the workplace (own compliation assessment based on BORG RPE scale according to (Hefferele and Kluth, 2019))

Please estimate the workload of your current professional activity. Please tick the appropriate boxes. Only your personal feelings are important! During the test, we want you to evaluate your perception of effort. You should use the BORG scale, where 6 means “no exertion at all” and 20 means “maximum exertion”. The number 9 is a “very light” physical effort, like walking slowly for a few minutes. The number 13 on this scale is already a “somewhat hard” strain. But it still works well and you should have no problems to continue. The number 17, " very hard ", is really very exerting, you can still continue, but you have to push yourself very hard. The number 19 is already an “extremely hard” strain. For most people this is as strenuous as the greatest physical effort they have ever experienced. Try to assess your feeling of exertion as honestly as possible. You should neither underestimate nor overestimate it. Some people are a bit too insensitive or want to be 'brave' and judge the effort too low. Try to feel the effort as you perceive it. We are only interested in your own feeling of achievement and effort. Look at the scale and the names and give us a number

No exertion at all	Extremely light		Very light		Light		Somewhat hard		Hard (heavy)		Very hard		Extremely hard	Maximum exertion
6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

How do you rate the perceived stress of the activity using the BORG scale?	**WITHOUT** THE EXOSKELETON	**WITH** THE EXOSKELETON
Total stress and strain		

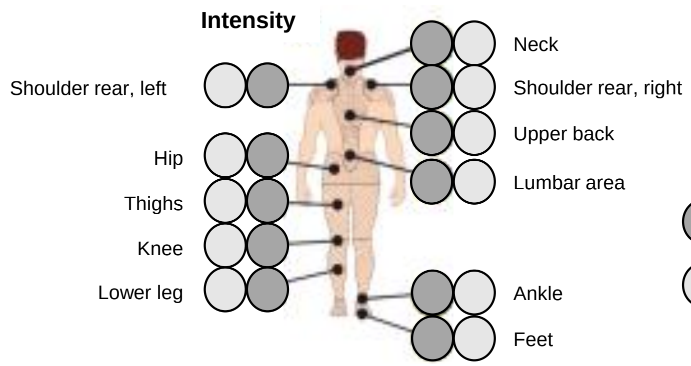
Please consider whether the following characteristics or stress factors occur at your workplace. If not you can leave the field blank		How do you rate the perceived stress of the activity using the BORG scale?	
		WITHOUT THE EXOSKELETON	**WITH** THE EXOSKELETON
0	*Example: Overhead work*	*11*	*11*
1	Forced posture (lack of space)		
2	Bent posture		
3	Squatting posture		
4	Kneeling posture		
5	Overhead work		
6	Standing		
7	Sitting		
8	Walking		
9	Holding of heavy loads (>5s)		
10	Carrying of heavy loads (>5m)		
11	Lifting of heavy loads		
12	Pulling / pushing of heavy loads		
13	Overall stress and strain		

Page 2/3

Physical stress and support from the technology in the workplace (own compilation based on BORG RPE scale and body map from (Groos *et al.*, 2020, p. 78))

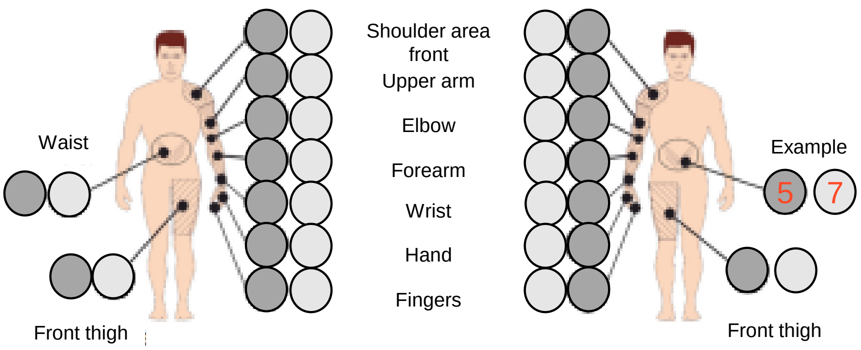
Please estimate the strain of your current professional activity. Please tick the appropriate boxes. Only your personal feelings are important! As a reminder once again the BORG scale:

No exertion at all	Extremely light		Very light		Light		Somewhat hard		Hard (heavy)		Very hard		Extremely hard	Maximum exertion
6	7	8	9	10	11	12	13	14	15	16	17	18	19	20



Perceived strain **WITHOUT** the exoskeleton

Perceived strain **WITH** the exoskeleton



Please use the provided 7-point scale to assess to what extent the following statements apply to you (own compilation based on SUS scale)

		Fully disagree	Disagree	Disagree a little	Neither	Agree a little	Agree	Fully agree
1	The exoskeleton has supported me in the majority of my activities.	○1	○2	○3	○4	○5	○6	○7
2	The exoskeleton is suitable for my workactivities.	○1	○2	○3	○4	○5	○6	○7
3	The exoskeleton hinders me in the majority of my activities.	○1	○2	○3	○4	○5	○6	○7
4	I would use the exoskeleton.	○1	○2	○3	○4	○5	○6	○7
5	I want my company to procure the technology fro me.	○1	○2	○3	○4	○5	○6	○7

Final remarks?

Page 3/3

12.9 PUBLICATION

Number	Citation
1	Wolf M., Herstätter P., Ramsauer C. (2019): Using the IIM LEAD factory to identify countermeasures for the demographic challenge. 2019. Procedia Manufacturing Volume 31,2019, Pages 123-128 https://doi.org/10.1016/j.promfg.2019.03.026
2	Wolf M., Ramsauer C. (2019): Towards an Age-Differentiated Assessment of Physical Work Strain. In Bagnara S., Tartaglia R., Albolino S., Alexander T., Fujita Y. (eds) Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018). IEA 2018. Advances in Intelligent Systems and Computing, vol 826. Springer Cham, Pages 189-205. DOI: https://doi.org/10.1007/978-3-319-96065-4_22
3	Wolf M., Kleindienst M., Ramsauer C. (2018): “Future industrial challenges – the demographic change and measures for elderly workers in Industry 4.0”. Annals of Faculty Engineering Hunedoara –International Journal of Engineering, 16(1), Pages 67-76. Online: http://annals.fih.upt.ro/pdffull/2018/ANNALS-2018-1-09.pdf
4	Wolf M., Kleindienst M., Ramsauer C. (2017): “Future industrial challenges – the demographic change and measures for elderly workers in Industry 4.0”. Book of abstracts of the 9th International Conference on Management of Technology – Step to Sustainable Production (MOTSP 2017) Dubrovnik, Croatia. ISSN: 1849-7586
5	Kleindienst, M., Wolf, M., Ramsauer, C., & Pammer-Schindler, V. (2016): „Industry 4.0: What Workers Need and What ICT Can Give –An Analysis”. Proceedings of the 16th International Conference on Knowledge Technologies and Data-driven Business (I-KNOW 2016), Messe Kongress Graz
6	Kleindienst M.; Wolf M.; Ramsauer C.; Winter E.; Zierler C. (2016): “Demographic change and its implications for ergonomic standardization”. Proceedings of the 6th international Ergonomics Conference 2016 (Ergonomics 2016), Zadar, Pages 179-188. ISSN 1848-9699