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HOW TO COPE WITH UNCERTAINTY IN OPERATIONS
Learning factory based teaching approach in the context of agile operations and manufacturing industry

DOCTORAL THESIS

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AFFIDAVIT

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Abstract

Between 1960 and 2000 the volatility of revenues in US firms doubled. This trend continued until today. Further, uncertainty and volatility are considered as the 'new normal' in business since the financial crisis in 2008. In addition to market and customer volatility, major disruptions are accelerating at an increasing rate. Most recently, the COVID-19 pandemic influenced every aspect of daily life and business. However, all these developments play a two-part role – as opportunities and threats – to companies and their operations. Therefore, coping with uncertainties in operations is a necessary means to achieve a competitive advantage.

Agile operations is a concept to cope with uncertainties. Agility from an operational point of view is seen as the capability of a company to prepare proactively for uncertainties and to react quickly to changes to optimize the economic situation. Literature highlights the two main pillars of (1) 'sensing' to early detect change and (2) 'responsiveness' as the ability to quickly reallocate resources to gain competitive advantages. Related activities require cross-functional cooperation across the value chain as agile operations sees the company as part of an overall system and not as an isolated player in the market. Considering the broad scope of this concept, a systematic approach designing agility is required. However, current literature focuses more on 'what' agility systems should contain rather than on 'how' to design such a system.

This is where the present research extends current knowledge by investigating how to develop competences to design an agile operations system. Training and competence development are important enablers for operational improvement programs (e.g. lean, six sigma). Literature points out that specifically so-called 'learning factories' emphasize competence development in the field of production process optimization. Such learning factories are close-to-reality models of value chain sections and complex learning environments. The learning factory approach gets attention from companies to qualify specialists on the shopfloor as well as on the top-management level. The overall research purpose of this thesis is thus to develop a training course to design an agile operations system in such a learning factory environment.

This research study applied an action research approach. Therefore, the empirical inquiry consisted of two action research cycles of constructing and planning action; taking action and data acquisition; and the subsequent evaluation of taken actions. 'Actions' in this context refer to conducted training courses throughout this research study. In total 50 participants conducted the developed training approach at Graz University of Technology's LEAD Factory. Overall, the main findings demonstrate that a learning factory based training course characterized by an authentic problem situation, the alternation of thinking and doing, and opportunities to reflect taken actions enables successful competence development regarding the design of an agile operations system.

Several teaching elements were developed and tested throughout this research study to achieve these charateristics. Especially, the developed virtual extension to the physical learning factory setting enabled the mapping of the subject matter of agile operations and its broad scope. These teaching elements, the identified and formulated competences to design an agile operations system and findings of conducted training actions extend current literature and contribute to practice. Besides contributions to the research field of learning factories, the developed and tested training course extends agile operations literature empowering practitioners *to cope with uncertainty in operations*.

Kurzfassung

Zwischen 1960 und 2000 hat sich die Volatilität der Umsätze in US-Firmen verdoppelt. Dieser Trend hält bis heute an. Seit der Finanzkrise 2008 ist Volatilität die neue Normalität im Geschäftsleben. Zu der Markt- und Kundenvolatilität kommen immer häufiger Disruptionen. Zuletzt beeinflusste die COVID-19-Pandemie jeden Aspekt des Privat- sowie Geschäftslebens. All diese Entwicklungen bieten sowohl eine Chance als auch eine Bedrohung für Unternehmen. Daher ist die Bewältigung von Unsicherheiten ein notwendiges Mittel, um einen Wettbewerbsvorteil zu erzielen.

Agile Operations (AO) ist ein Konzept um mit Unsicherheiten umzugehen. AO ist die Fähigkeit eines Unternehmens, sich proaktiv auf Unsicherheiten vorzubereiten und schnell auf Veränderungen zu reagieren, um die wirtschaftliche Situation zu verbessern. Die Literatur hebt zwei Themengebiete hervor: (1) "Sensing", um Veränderungen frühzeitig zu erkennen und (2) "Responsiveness" als Fähigkeit Ressourcen schnell umzuverteilen, um Wettbewerbsvorteile zu erlangen. Zu den damit verbundenen Aktivitäten gehört die funktionsübergreifende Zusammenarbeit über die gesamte Wertschöpfungskette. AO sieht ein Unternehmen als Teil eines Gesamtsystems und nicht als isolierten Akteur auf dem Markt. In Anbetracht des breitgefächerten Umfangs dieses Konzepts ist ein Systemansatz erforderlich. Die aktuelle Literatur konzentriert sich jedoch eher darauf, was ein Agilitätssystem enthalten sollten, als darauf, wie ein solches System zu gestalten ist.

Hier erweitert die vorliegende Arbeit das aktuelle Wissen, indem sie untersucht, wie man Kompetenzen zur Gestaltung eines AO-Systems entwickelt. Training und Kompetenzentwicklung sind wichtige Faktoren für Verbesserungsprogramme (z.B. Lean, Six Sigma). In der Literatur wird darauf hingewiesen, dass insbesondere Lernfabriken die Kompetenzentwicklung im Bereich der Produktionsprozessoptimierung fördern. Lernfabriken sind realitätsnahe Modelle von Teilbereichen der Wertschöpfungskette und komplexe Lernumgebungen. Lernfabriken rücken in den Fokus von Unternehmen um Mitarbeiter sowohl auf Shopfloor- als auch auf der Top-Management Ebene zu qualifizieren. Das übergeordnete Forschungsziel dieser Arbeit ist die Entwicklung eines Trainingskurses zur Gestaltung eines AO-Systems in einer solchen Lernfabrikumgebung.

Diese Forschungsstudie wendet einen handlungsorientierten Forschungsansatz an. Die empirische Untersuchung besteht aus zwei Forschungszyklen (Konstruieren und Planen von Handlungen, dem Durchführen von Handlungen und der Datenerfassung, sowie der anschließenden Auswertung der durchgeführten Handlungen). „Handlungen" beziehen sich im Kontext dieser Arbeit auf die durchgeführten Trainingskurse. In Summe nahmen 50 TeilnehmerInnen an dem entwickelten Trainingsansatz in der Lernfabrik der Technischen Universität Graz (LEAD Factory) teil. Insgesamt zeigen die Hauptergebnisse dieser Arbeit, dass ein auf einer Lernfabrik basierendes Training, das durch die Abbildung einer authentischen Problemsituation, einem Wechsel von Denken und Handeln, und Gelegenheiten zur Reflexion der durchgeführten Handlungen bietet, gekennzeichnet ist, eine erfolgreiche Kompetenzentwicklung hinsichtlich der Gestaltung eines AO-System ermöglicht.

Um diese Merkmale zu erreichen, wurden im Rahmen dieser Forschungsstudie mehrere Unterrichtselemente entwickelt und erprobt. Insbesondere die entwickelte virtuelle Erweiterung der physischen Lernfabrik ermöglichte die Abbildung des AO Konzeptes. Diese Lehrelemente, die identifizierten und formulierten Kompetenzen zur Gestaltung eines AO-Systems und die Erkenntnisse aus den durchgeführten Trainingsmaßnahmen erweitern die aktuelle Literatur und leisten einen Beitrag zur Praxis. Der entwickelte und getestete Trainingskurs befähigt Praktiker *mit Unsicherheiten umzugehen*.

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CHAPTER 1
Introduction

Chapter 1 gives an introduction to this thesis. Subsection 1.1 describes the initial motivation for this research. Section 1.2 introduces the objective of this thesis. Finally, section 1.3 outlines this thesis with a comprehensive description of the main chapters.

1.1 Situation - the need for agile operations

Nowadays there is an ever-increasing pace of unexpected changes in the business landscape (Dobbs et al. 2015, p. 85). According to *Reeves et al. 2015* especially continuous substantial technology changes, unpredictability of customer needs, existing industry structures and global competition drive volatile demands and forecasts that are mostly not any longer robust enough to create sound plans. Based on these measures the authors argue that turbulence and uncertainty in business is more frequent, more intense and longer than in the past. As example serves the percentage of firms dropping out of the top three revenue rankings per industry. From 3% drop-out rate in 1961 to 17% in 2002 and 8% in 2013. Further, the probability that non market-share leaders are more profitable increased. (Reeves et al. 2015, pp. 65–66)
These findings support *Rogoff and Gertler 2006* who showed that the average length of industry-leadership is radically decreasing over the past decades (Rogoff and Gertler 2006, p. 197). Several research studies conclude that with increasing volatility in customer demand and uncertain economic circumstances the marketplace turns into a battlefield (Rogoff and Gertler 2006, p. 197). *Heifetz et al. 2009* stated that the financial crisis 2008 and the following recession are just setting a stage for continuing crisis of unfamiliar challenges and that the mix of urgencies, high risks and the increasing uncertainty will stay as 'new normal' (Heifetz et al. 2009, p. 62).

Besides customer and market volatility *Sheffi 2015* points out that the rate of major disruptions and 'unknown unknowns' are accelerating across the world (Sheffi 2015, p. 354). The Global Facility for Disaster Reduction and Recovery (GFDRR) – a World Bank organization – reports that: *"[…] annual total damage (averaged over a 10-year period) has increased tenfold between 1976-1985 and 2005-2014, from US$ 14 billion, to more than US$ 140 billion."* (Global Facility for Disaster Reduction and Recovery 2016, xiv). *Kleindorfer and Saad 2005* state that such disruptions occur due to (1) operations contingencies - equipment malfunctions or systematic failures; (2) natural hazards - e.g. earthquakes, hurricanes or tsunamis; and (3) terrorism and political instability (Kleindorfer and Saad 2005, pp. 54–55).

Baker et al. 2020 outlined in their working paper "COVID-induced economic uncertainty" that the COVID-19 pandemic causes a new level of uncertainty. More less every aspect of life and business is affected: infectiousness, prevalence and lethality of the virus; testing capacity and availability of potential vaccines; impact on health care systems; impact of regional lockdowns across the globe on economies; the speed of recovery and its impact on business survival as well as other COVID-19 related factors influence our daily life. (Baker et al. 2020, p. 3)

However, all of these dynamics play a two-part role - as threats and opportunities - to a company's competitive advantage (Yang and Liu 2012, pp. 1039–1040).

Thach 2012 and *Leslie and Canwell 2010* conclude that the managerial capability to foresee, prevent, manage and overcome disruptions and crisis is crucial for corporate success (McCarthy 2014, pp. 56–57). *Dervitsiotis 2004* points out that today's management thinking relies still on the evaluation of 'making profits' as the main criterion for corporate success. Except that managerial decisions based on such thinking are not effective in times of uncertainty and change. (Dervitsiotis 2004, pp. 807–808)
Dealing with dynamic change has been a topic for academia and research in the past decades (Sherehiy and Karwowski 2014, p. 467). Companies must be capable to respond quickly to changing boundary conditions within their operating system (Wang et al. 2012, p. 270). One approach to cope with uncertainties in operation is the concept of agile operations (Sharifi and Zhang 2001, p. 774).

Since its first definition by Nagel 1991 agile operations has become growing recognition for its transformational advantages (Brosseau et al. 2019, 2). *Sherehiy and Karwowski 2014* state that "A*mong proposals of how to deal with the uncertain and unpredictable environment the notion of agility is the most predominant and popular lately.*" (Sherehiy and Karwowski 2014, p. 466) Research in the last years outlined that agile characteristics have a positive influence on the level of a company's competiveness (Ren et al. 2003, p. 494; Yusuf et al. 2003, p. 623). *Yusuf and Adeleye 2002* state that "*[…] lean production is under threat […]*" and that due to increasing market volatility companies should focus on agile operations (Yusuf and Adeleye 2002, p. 4560). The quantitative approach to describe the impact of agile operations shows that agile companies are more profitable compared to their peer group (Deubel, 2017 p. 103).

Reeves et al. 2015 describe the case of Zara - a major player in the fashion industry – as an example of the advantage when adapting to an unpredictable environment and applying agility. The majority of Zara's competitors try to predict customers demand (style, cuts, colors, etc.) each season with the downside that in most cases the forecasts are wrong and retailers have to discount up to the half of their stock each season. Zara, however, does not rely on predictions but it is able to perform experiments each day in their shops with in small batches produced fashion articles. Zara just selects the top-runner products for scale up. This is possible because Zara shortened its supply chain to be able to design, produce and deliver their products in five months less than the industry average lead-time. Therefore, Zara is able to produce new products during the season, which generated margins constantly 100% above industry average in that period. (Reeves et al. 2015, pp. 61–63)

Agility is the necessary means for surviving and competing if the way business is done is changing fundamentally (Schönsleben 2000, p. 39). However, *"[…] moving to an agile operating model is tough, especially for established companies.*" (Brosseau et al. 2019, p. 2)

1.2 Opportunity and research purpose

Operations improvements and sustaining change within organizations are made possible through engagement and further development of employees (Chiarini 2011, p. 332). This statement is supported as well-known operations improvement approaches like lean, six sigma, total quality management or business process reengineering stress training and education as necessary basis. (Mi Dahlgaard-Park and Dahlgaard 2006, pp. 273–274; Chiarini 2011, p. 332).

Related to the importance of learning in operations management literature states that the concept of agile operations can be seen as capability (Gunasekaran 1998), p. 1223). Strengthening this research conclusion, *Sull 2009* points out that empowered people with right capabilities are key to respond creatively and powerful to ever increasing volatility (Sull 2009, p. 190). Furthermore, *Brosseau et al. 2019* support these arguments and state: *"Most organizations require existing staff to take on these new roles or responsibilities, and as such, need a way to build new skills and capabilities."* (Brosseau et al. 2019, 8, 2019)

Despite the importance of knowledge creation, *Cachay et al. 2012* show in their study that success rates of traditional teaching methods (e.g. theoretical lectures) have limited effects in transporting operations management topics (Cachay et al. 2012 2012, p.1150). Due to this fact, *Abele et al. 2015b* point out that learning approaches are needed that (1) involve learning environments close to realistic operations; (2) realize modern learning processes close to industrial practices; and (3) further develop industrial practice by transporting up-to-date manufacturing knowledge (Abele et al. 2015b, p. 1). Learning factories are such close to reality learning environments (Abele et al. 2007, p. 741) and have shown in the past that they enhance operations management competence development (see e.g. Abele et al. 2010b, p. 240; Cachay and Abele 2012), especially by transporting the principle of experiential learning (Zan et al. 2015, p. 333).

Experience as key to develop competences and the principle of learning factories as learning environment enforcing experiential learning might enable a successful agile transformation. Thus, a learning factory focusing on agile operations might become what *Brosseau et al. 2019* call a "*[…] capability accelerator to retrain and reorganize staff, make the agile idea common to all, and develop the right skills across the organization.*" (Brosseau et al. 2019, 8)

The following statement defines the research purpose of the present thesis.

"Enabling competence development to design an agile operations system to cope with uncertainty in operations through the development of a training course using experiential learning principles and a learning factory setting."

1.3 Structure and outline of the thesis

Chapter 1 introduces the initial situation and states the research purpose of this thesis. Further, the first chapter outlines the relevant literature fields of this research, namely **agile operations**, c**ompetence development** and **learning factories**. Finally, the chapter describes in brief the strucutre of this thesis.

Chapter 2 'fundamentals' presents the existing knowledge of the research fields of interest in detail. First, it defines basic terms and the understanding of the concept of agile operations is deepened to provide a solid basis for this research. The concept of agile operations in relation to this research is summarized in subsection 2.2.8.

Second, this chapter describes the concept of competence and the related topics 'learning' and 'experiential learning' in more detail. The objective of these sections is to derive a common understanding of contexts. The sections related to competence development are summarized in subsection 2.3.4.

Third, chapter 2 introduces the research field of 'learning factories'. In dedicated subsections the term 'learning factory' is defined, its principles and potentials are described, its interrelation to competence development is outlined and limitations of the concept of learning factories in literature are described. Finally, main learnings from learning factory related literature are summarized in subsection 2.4.6.

Fourth, chapter two reviews related studies to this research. This includes studies to map different operations management subject matters in learning factories and guiding frameworks to develop such learning factory training courses. The objective is to gain learnings from previous research and to provide the basis to choose a structured guiding procedure to follow in the empirical part of this research work. The related closing subsection 2.5.3 discusses gained insights.

Finally, chapter 2 closes with an interim conclusion on the intersections of the reviewed topics agile operations, competence development, experiential learning and learning factories relevant to this research. The interim conclusion serves as basis to formulate the underlying research questions of this thesis.

Chapter 3 'aims and objectives' formulates based on the conducted literature study the research leading questions. The research questions address the characteristics of a learning factory based course to develop competences regarding the design of an agile operations system. Further, research question two aims to discuss how learning factories support the intended competence development. Further, subsections outline the intended contributions to literature and practice as well as delimitations of this research.

Chapter 4 'methodology' first describes general considerations concerning the research approach of the present study at hand. Further, the first subsection outlines considerations concerning the evaluation approach and data collection methods. Then, this chapter describes the chosen research approach of 'action research' and its implications on this study. In the following subsection, the elaborated research framework shows *what* this research inestigates. Further, the research framework serves as basis for a structured data collection and subsequent analysis. Finally, this chapter outlines conducted research steps and the approach to data collection and analysis in detail.

Chapter 5 ‘conception’ describes the developed training course addressing competences to design an agile operations system. First, taken steps according to the chosen guiding framework to develop a learning factory based training course (proposed by *Tisch 2018*) is outlined. Second, the formulated main competence is broken down into its consisting elements (sub-competences, knowledge elements and observable actions) based on a literature study. Third, this chapter describes the derivation of requirements to the learning environment highlighting the broad scope of the subject matter of agile operations and its interferences with current limitations of learning factories. Then, the characteristics of the developed training course are outlined. This includes elements like course organization, applied teaching methods or the sequence of learning situations. Finally, this chapter introduces developed extensions to the learning environment specifically for the subject matter of agile operations to overcome identified limitations. Chapter 5 closes with a brief summary of the research phase of conception.

Chapter 6 ‘results’ presents the gathered data from conducted training actions and introduces in brief interim conclusions derived further developments based on retrieved results. The training actions are set according to the chosen research design of action based research. The author of this research conducted the trainings at Graz University of Technology’s LEAD Factory. Finally, this chapter closes with introducing results from a conducted quasi-experiment comparing retrieved results from the learning factory treatment with a classic frontal lecture treatment.

Chapter 7 ‘conclusion’ summarizes the main results regarding the formulated research questions based on the retrievied results of the literature study and the conducted training actions. Second, this chapter discusses the research quality in terms of validity, reliability and objectivity of the present study.

Finally, chapter 8 ‘summary and outlook’ summarizes first the initial situation, the theoretical basis and the research aims. The following subsection outlines the chosen research methodology and the validation approach. Then, this final chapter summarizes the contributions to literature and practice as well as limitations of the research study at hand. Section 8.2 outlines potential future research areas related to this thesis.

CHAPTER 2

Fundamentals

Chapter 2 deals with existing knowledge regarding the fields of interest in detail. Section 2.1 defines the scope and focus of the literature review. Section 2.2 deepens the understanding of the concept of agile operations and related concepts to derive a solid basis for this research. Section 2.3 maps the basics of competence development with a strong focus on experiential learning and related methods to increase participants learning. Section 2.4 introduces learning factories as learning environments. In following section 2.5 related studies to this research are reviewed. Each section closes with a brief summary and gained learnings relevant to this thesis. Chapter 2 is completed by an interim conclusion of existing knowledge concerning the consulted literature.

At the Institute of Innovation and Industrial Management (IIM) at Graz University of Technology previous research concerning the topic of 'agile operations' was conducted. Throughout the years 2014 to 2017 dedicated researchers from academia as well as practitioners jointly worked on the topic of agile operations. The research activities resulted in authoring a dedicated book "Erfolgsfaktor Agilität" (*Ramsauer et al. 2017*) and four related doctoral thesis (Schurig 2016; Rabitsch 2016; Heldmann 2018; Pointner 2018). Results of these research activities on the topic of agility are considered as the starting point for the present thesis at hand.

2.1 Scope and focus of literature fundamentals

As collecting and analyzing information is key to research in order to increase the understanding of a specific topic (Creswell 2007, p. 3) the hereinafter presented review of relevant literature was carried out and further advanced throughout the proceeding of this dissertation project.

As each research project should contribute to existing knowledge a sound understanding of existing research is mandatory (Karlsson 2016, p. 19). This research deals with two main research streams: (1) the concept of agile operations and (2) competence development. The cluster of competence development is further divided into 'basics of competence development', 'learning factories' and 'related studies to this research'. Of specific interest are insights about the relation of (1) **'competence development' and 'learning factories'** as well as (2) **'agile operations' and 'competence development'** (and 'learning factories').

Figure 1 depicts the relevant research streams and related sections of this thesis.

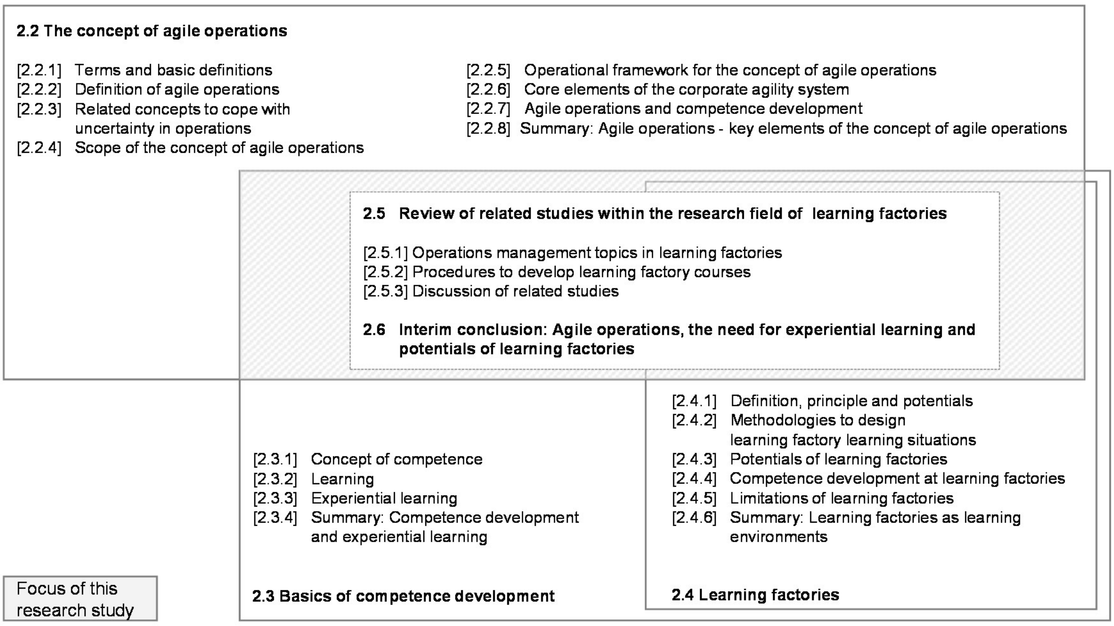

Figure 1: Scope of literature review (own illustration)

The concept of agile operations:

The first research field provides a solid theoretical base of the topic of agile operations. Definitions, related literature and frameworks of agile operations are introduced. A framework and definition of agile operations is comprehensibly chosen to clarify how this topic is considered throughout this research. The chosen framework is further divided into core elements. The subchapters dedicated to these core elements review literature, identify, and summarize relevant aspects for the further course of this research.

Basics of competence development:

Basic definitions of relevant terms and a review of learning theories are necessary to integrate this work into the existing literature. Section 2.3.3 addresses experiential learning in detail due to its relevance for this research. Frameworks of experiential learning models and related learning methods are reviewed in order to identify their potentials and implications for this research.

Learning factories:

The third research area concerns with learning environments. Learning environments are one particular aspect of the overarching research area ‘competence development’. However, due to the importance of this topic to this research a strong emphasis is put on related literature. Dedicated sections introduce the learning factory priniciple, potentials and limitations of learning factories and current practices concerning competence development at learning factories.

Review of related studies:

Respective subchapters review related studies within the subject of competence development in learning factories in order gain valuable insights for the further phases of the present thesis at hand. A focus is put on research work implementing operations management topics to learning factories. Further, current research results concerning guiding frameworks to develop related trainings in a learning factory based setting are identified and reviewed.

2.2 The concept of agile operations

First, this chapter defines relevant terms related to manufacturing. Second, it introduces concepts to cope with uncertainty in operations, defines the concept of agile operations in detail and delimitates the topic of agile operations from related concepts. Third, this chapter outlines the scope of agile operations. Fourth, existing frameworks of agile operations are discussed and a framework as base for this research is chosen. Fifths, to breakdown the concept of agility to an operational level the main building blocks are outlined. Further, this chapter reviews literature concerning agile operations and competence development. This chapter concludes with a brief summary of the key elements of the concept of agile operations.

2.2.1 Terms and basic definitions

In the following the basic terms 'production', 'manufacturing', 'operations', 'operations strategy', 'supply chain', 'value network' and 'uncertainty' are defined with respect to the research focus of this thesis. The objective of this section is to create a common understanding for terms used throughout this thesis.

Production and manufacturing

Production is defined as *"[...] the making of something new – either tangible ('products') or intangible ('services')"* (Hitomi 1996, p. 4). *Gutenberg 1963* defines production as combination of the three elementary production factors: (1) human work/labor, (2) machines and (3) materials (Gutenberg 1963, pp. 1–10). Further, *Hitomi 1996* defines production in a narrow sense as the transformation process of (raw) materials into products using labor, production means and information as inputs (Hitomi 1996, p. 4). The International Academy for Production Engineering (CIRP) defines 'production' as "*The pure act or process (or the connected series of acts or processes) of actually physically making a product from its material constituents [...]*" (CIRP (ed.) 2020, p. 17) – this definition is used in the course of this thesis.

Manufacturing as term is often used interchangeable with production (CIRP (ed.) 2020, p. 9). In spite of that, it should be understood in a broader sense and encompasses productive activities from *"[...] planning, design, procurement, inventory, marketing, distribution sales, management."* (Hitomi 1996, p. 4) Further, manufacturing includes necessary managerial functions (CIRP (ed.) 2020, p. 9). Therefore, the scope of 'manufacturing' is seen broader than the scope of 'production' throughout the present thesis at hand.

Operations and operations strategy

Slack et al. 2010 describe operations besides marketing/sales and product development as one of the three core functions any organization is build upon. Operations is responsible for the production and the delivery of products. Further, they define "*[...] the operations function as comprising all the activities necessary for the day-to-day fulfilment of customer requests. This includes sourcing products and services from suppliers and transporting products and services* *to customers."* (Slack et al. 2010, 1:5-6) Therefore, operations is more than production and takes place across corporate functions (Brown 2001, p. 6). Subsequently working together across functional boarders within an organization is key to modern operations management (Slack et al. 2010, 1:5-6).

Strategy in business context refers to *"[…] the total pattern of the decisions and actions that influence the long-term direction of the business."* (Slack et al. 2010, 62) Thus, operations strategy is the strategic perspective dealing with long-term decisions and actions of how resources and processes in operations are managed (Slack and Lewis 2015, p. 9). However, *Brown 2001* states that in operations literature the main focus is on tools to improve day-to-day operations and that operations literature ignores the strategic importance of the topic. Further, the author argues that to compete in today's business environment business and operations strategy need to be aligned. (Brown 2001, p. 44)

Supply chain and value chain

Slack et al. 2010 define a supply chain as "*a linkage or strand of operations that provides goods and services through to end-customers […]"* (Slack et al. 2010, p. 668). Further, they emphasize that an organizations operation is a crossing point for several supply chains (Slack et al. 2010, p. 668). Supply chains consist of individual partners with equal rights (Stadtler et al. 2015, p. 15).

Sturgeon 2001 defines 'value chain' as "*the sequence of productive (i.e. value-added) activities leading to and supporting end use*" (Sturgeon 2001, p. 11). However, he further states that the terms 'supply chain' and 'value chain' are often used interchangeable (Sturgeon 2001, p. 11). Throughout this research, the terms 'supply chain' and 'value chain' are used separately. Whereas the definition of *Slack et al. 2010* is used for the term 'supply chain', 'value chain' is used in a broader sense describing value networks according to *Sturgeon 2001*.

Value networks

In order to be competitive companies build temporary cooperations across the value chain to specialize their own activities (Westkämper and Decker 2006, p. 34). In literature four different types of value networks related to manufacturing exist (Rudberg and Olhager 2003, p. 35). *Rudberg and Olhager 2003* describe - besides the single organization with a single plant - that there is a distinction of the number of involved network-partners from single partner networks ('intra-firm network' with multiple sites) to multiple partners networks with single-sites of each partner ('supply chain' – see previous section) and multiple sites per involved organization ('Inter-firm network'). Further they emphasize that each of the identified type of network contains various degrees of complexity (Rudberg and Olhager 2003, p. 35).

Following Figure 2 depicts these four types according to the configuration of value networks.

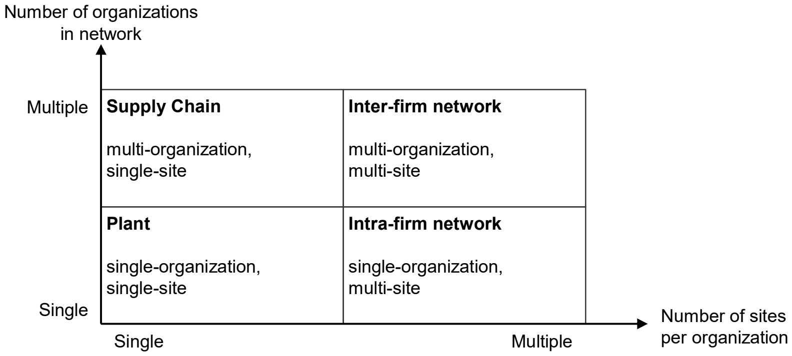

Figure 2: Types of value networks (based on Rudberg and Olhager 2003, p. 35)

Due to no further distinction throughout this research, the terms ‘value or production network’ or ‘value chain’ are used synonymously to intra-firm-, and inter-firm value networks.

Uncertainty

Knight 1921 states in his research that uncertainty is a situation in which the probability of events is unknown and that uncertainty is dependent mostly upon progressive change (Knight 1921, p. 368). *Gass and Fu 2013* define uncertainty as *“[...] limited knowledge about future, past or current events.”* (Gass and Fu 2013, p. 395) Sources for uncertainties in today’s business environment evolve e.g. from volatility in demand, volatility of input factor prices to disruptions of supply chains or internal disruptions (Alicke et al. 2014, pp. 37–38). Further, *Knight 1921* defines situations where probabilities of outcomes are known (‘measurable uncertainties’) as ‘risk’ whereas ‘(true) uncertainties‘ refer to situations where it is impossible to identify numerical probabilities (Knight 1921, p. 46). However, in literature the distinction between the terms ‘risk’ and ‘uncertainty’ is an ongoing discussion since Knight’s definition in 1921 (LeRoy and Singell 1987, p. 395). Concerning this research, the terms ‘uncertainty’ and ‘risk’ are used synonymously. However, uncertainties like e.g. shifts in customer demand, factors of climate change, financial fluctuations, technological advances or political and regulatory factors cause disturbances to operations (Westkämper and Zahn 2009, p. 10). *Christopher and Holweg 2011* state that “*As of 2008, we have left an almost 30-year lasting period of stability behind and are now entering a period of turbulence that was last seen during the oil crisis of 1973.”* (Christopher and Holweg 2011, p. 67)

2.2.2 Definition of agile operations

Since the first publication about agility (to be more precisely: agile manufacturing) in 1991 by the Iacocca Institute the topic is discussed in academia and by practitioners (Prange and Heracleous 2018, pp. 1–2). The overall goal to enhance manufacturing and service processes of the initial concept stayed the same (Gunasekaran and Yusuf 2002, p. 1357). Throughout the past 30 years researchers performed literature reviews with different foci concerning the topic of agility. *Jin-Hai et al. 2003* describe the evolution of agile manufacturing focusing on available definitions of the term "agile manufacturing" itself. They conclude that " *[...] very different aspects of agility have been emphasized in the literature*" (Jin-Hai et al. 2003, p. 173). Further, *Narasimhan et al. 2006* state that literature discusses the topic of agility in different contexts - from a manufacturing capability to a strategic ability or to an overall business process. *Shin et al. 2015* performed a literature review to identify and explore research streams of agility like supply chain agility, organizational agility or strategic agility (Shin et al. 2015, p. 184). Table 1 summarizes definitions of different agility constructs.

Table 1:Definitions for agility constructs in literature (extended from *Jin-Hai et al. 2003; Shin et al. 2015 and Fayezi et al. 2017*)

Source	**Definition**
Nagel 1991, p.2	"A manufacturing system with capabilities (hard and soft technologies, human resources, educated management, information) to meet the rapidly changing needs of the marketplace (speed, flexibility, customers, competitors, suppliers, infrastructure, responsiveness)."
Booth 1996, p. 107	"Companies seek to combine the advantages of time compression with techniques to reduce the costs of variety while remaining adaptable to future changes. The intention is to be able to offer almost instant delivery of small quantities of goods with individual specifications."
Roth 1996, p. 30	"The capability to produce the right products at the right place at the right time at the right price."
Cho et al. 1996, p. 323	"Agile manufacturing can be defined as the capability of surviving and prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services."
Dyer and Shafer, p. 6	"Organizational agility is the capacity to be infinitely adaptable without having to change. It is viewed as a necessary core competence for organizations operating in dynamic external environments."
Bullinger 1999, p. 11	"Agility means mobility in an organization's behavior towards the environment and can therefore be understood as an extensive answer to continually changing markets. Agile companies are in a process of constant re-determination, or self-organization, self-configuration, and self-teaming."
Yusuf *et al.*, 1999, p. 37	"Agility is the successful exploration of competitive bases (speed, flexibility, innovation, pro-activity, quality and profitability) through the integration of reconfigurable resources and best practices in a knowledge-rich environment to provide customer-driven products and services in a fast-changing market environment."
Sharifi and Zhang 1999, p. 9	"The ability to cope with unexpected changes, to survive unprecedented threats of business environment, and to take advantage of changes as opportunities."
Christopher and Towill 2001a, p. 236	''Agility is a business-wide capability that embraces organizational structures, information systems, logistics processes and in particular mindsets."
Narasimhan et al. 2006, p. 443	"Production is agile if it efficiently changes operating states in response to uncertain and changing demands placed upon it"
Swafford et al. 2006a, p. 119	"Value chain agility is achieved through the synergies among the product development, procurement, manufacturing, and logistics processes."
Swafford et al. 2006b, p. 172	"Supply chain agility as the supply chain's capability to adapt or respond in a speedy manner to a changing marketplace environment."

Continued

Source	Definition
Overby et al. 2006, p. 121	"Enterprise agility is defined as the ability of firms to sense environmental change and respond readily. As such, enterprise agility consists of two components: sensing and responding."
Doz and Kosonen 2008, p. 96	"Focus on how to prevent stagnation and painful transformations so that companies do not become elephants that need to learn to dance."
Li et al. 2008, p. 421	"Agility is the result of integrating an alertness to changes (opportunities/challenges) – both internal and environmental – with a capability to use resources in responding (proactively/reactively) to such changes, all in a timely, and flexible manner."
Braunscheidel and Suresh 2009, p. 136	"Agility is viewed as a disruption risk management tactic that enables the firm and its partners to respond rapidly to market place changes, and to respond rapidly to both potential and actual disruptions in the supply chain."(Braunscheidel and Suresh 2009, p. 136)
Vickery et al. 2010, p. 7028	"Supply chain agility is defined as rapid responsiveness to the needs and wants of customers and potential customers."
Roberts and Grover 2012, p. 580	"Customer agility is the degree to which a firm is able to sense and respond quickly to customer-based opportunities for innovation and competitive action."
Schurig 2016, p. 64	"Agility in manufacturing is the capability of a company to prepare proactively for uncertainties and react quickly to changes to optimize the economic situation by leveraging the whole value chain."
Prange and Heracleous 2018, p. 16	"Operational agility is the ability to change organizational structures, processes, systems, and culture to align with changing strategic priorities."

As Table 1 shows, the topic of 'agility' is broad, the general understanding is partly diverging and research focuses on several target areas. However, *Vázquez-Bustelo et al. 2007* state that due to the variety of definitions in literature it is necessary to consider those definitions simultaneously to understand the concept of agility (Vázquez-Bustelo et al. 2007, pp. 1305–1306). To narrow down the scope and to define a fundamental definition of 'agile operations' this research considers the work of *Schurig 2016*.

Based on a literature analysis *Schurig 2016* identifies the following key attributes of the agility concept: (1) capacity flexibility – lower and upper capacity limits of production; (2) profitability – to prosper and optimize profitability; (3) speed – time needed to adjust the output; and (4) proactivity – opportunity seeking and actively dealing with potential change. (Schurig 2016, pp. 60–63)
Due to these characteristics and the combination of available definitions *Schurig 2016* defines the concept of agility as: *"[...] the capability of a company to prepare proactively for uncertainties and react quickly to changes to optimize the economic situation by leveraging the entire production network."* (Schurig 2016, p. 64)

This definition incorporates amongst others elements of 'agile manufacturing' (e.g. Nagel 1991, p.2; Cho et al. 1996, p. 323; Sharifi and Zhang 1999, p. 9); 'supply chain agility' (e.g. Swafford et al. 2006b, p. 172;Li et al. 2008, p. 421); and 'enterprise' or 'organizational agility' (e.g. Dyer and Shafer, p. 6; Overby et al. 2006, p. 121).

The definition of the concept of agility by *Schurig 2016* is chosen as basis for this research due to its incorporation of several aspects of the broad topic of 'agility' (as proposed by *Vázquez-Bustelo et al. 2007* – see above) and the underlying goal of this research to not limit the present work to one functional area (e.g. supply chain). Rather, the present doctoral thesis considers the overall goal of the concept of agility to enhance manufacturing and service processes as proposed by *Gunasekaran and Yusuf 2002*. For this reason, the general terminology of 'agile operations' is used predominantly throughout this research work. However, the terms ‘agile manufacturing’ and ‘agility’ refer to the chosen definition and are understood interchangeable with ‘agile operations’ in the present thesis at hand.

2.2.3 Related concepts to cope with uncertainty in operations

The focus of this thesis lies explicitly on how to cope with uncertainties in manufacturing using the concept of agile operations. However, there exist various other concepts with partially similar objectives. In the following recently discussed approaches are introduced.

Manufacturing (or operational) flexibility
The definition by *Dey et al. 2019* rely on basic literature (e.g. *Gerwin 1993; Toni and Tonchia 1998; Beach et al. 2000; D'Souza and Williams 2000*) and describes ‘manufacturing flexibility’ as ability of an organization to effectively satisfy customer demand managing production means and uncertainty (Dey et al. 2019, p. 238). Further Swafford et al. 2006a states that manufacturing flexibility *“[…] enables production to respond to variability in demand, product design changes, process technology, and disruption in material supply.*” (Swafford et al. 2006a, p. 123). The responsiveness to changing conditions is enabled by the availability of pre-defined options (Swafford et al. 2006b, p. 174).

Strategic flexibility
Toni and Tonchia (1998) define ‘strategic flexibility’ in contrast to ‘operational flexibility’ as an organization’s ability to vary the combination of competitive priorities. Furthermore they state that a distinction exists sometimes due to the time horizon of the needed flexibility – short term for operational agility and medium to long-term for strategic flexibility (Toni and Tonchia 1998, 1609). *Narain et al. 2000* define ‘strategic flexibility’ as *“[…] how well a firm addresses and adapts its strategic decisions to unexpected changes in compete tive environment […]”* (Narain et al. 2000, p. 204).

Transformability and Changeability
Transformability as concept has evolved in Germany (German translation: “Wandlungsfähigkeit”) and was discussed e.g. by *Reinhart et al. 1999* as further development of the concept of operational flexibility. Transformability enables operations not only to react within a pre-defined scope but also rather to change efficiently even outside defined corridors (Reinhart et al. 1999, p. 22). *Wiendahl et al. 2007* enhanced this approach and coined the term ‘changeability’. Changeability is defined as “*[…] characteristics to accomplish early and foresighted adjustments of the factory’s structures and processes on all levels to change impulses economically.*” (Wiendahl et al. 2007, p. 785).

Resilience
Resilience is defined as “*The capacity for resisting, absorbing and responding, even reinventing if required, in response to fast and/or disruptive change that cannot be avoided.*” (McCann et al. 2009, p. 45) *Sheffi 2015* states that organizations have several strategic options to manage risks (in the meaning of ‘measurable’ uncertainties) and (general) resilience to respond to rare disruptions – so-called ‘unknown-unknowns’. *Sheffi 2015* further describes two complementary approaches to reduce risks and increase resilience. First, reduce the likelihood of occurrence of disruptions and second, to reduce the impact when disruptions have occurred (Sheffi 2015, pp. 62–63).

Further approaches discussed in literature are enterprise risk management *Hoyt and Liebenberg 2011*), adaptiveness (e.g. *Caesar et al. 2019*), re-configurability (e.g. *Napoleone et al. 2018*) or factory fitness (e.g. *Ferdows and Thurnheer 2011*).

Agile operations and related concepts to cope with uncertainty

As mentioned above the objectives of different concepts are partially overlapping. In literature exists an ongoing discussion among scholars about similarities, complementarities or distinctions between the individual concepts (see e.g. Wiendahl et al. 2015). In the following, the main difference in the scope of introduced concepts is presented.

The concept of agility from a production and product point of view goes beyond the approaches of flexibility, transformability (or changeability), adaptability or re-configurability (Schuh and Schmidt 2014, p. 19).

Manufacturing flexibility designed for pre-defined constraints on manufacturing system level is a reactive approach (Ramasesh et al. 2001, p. 537). Transformability builds upon flexibility, aims to enhance infrastructure, and processes on all factory levels to adapt the system outside pre-defined corridors in case of uncertainties (Wiendahl et al. 2007, p. 785). *Wiendahl and Hernández 2002* and *Heger 2007* state that the concept of agility in comparison to transformability and flexibility has the highest range to cope with uncertainties. Figure 3 shows these differences.

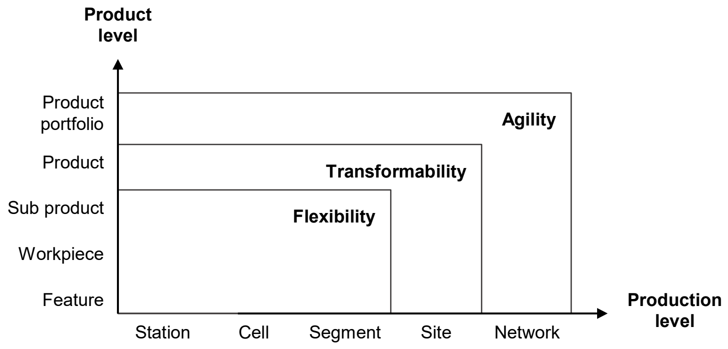

Figure 3: Scope of flexibility, transformability, and agility (Wiendahl et al. 2015, p. 108)

The main objective of resilience is to create robustness to external disruptions in order to 'bounce back' (Sheffi 2015 p. 55, Schurig 2017 p. 92). Enterprise risk management focus especially on potential business risks (Schurig 2017 p. 92). *Schurig 2017* argues that in contrast to these two approaches agility focuses additionally on opportunities to increase business profit in times of change and further shares the short-term aspects of flexibility and other operational approaches. Therefore, agility can be seen as an approach combining operational and strategic dimensions in order to quickly adapt to change (Schurig 2017, p.92). *Wiendahl et al. 2015* state that due to the impact of the concept of agile operations on the organization itself, it is influencing and influenced by strategies (Wiendahl et al. 2015, p. 109).

This research study does not further investigate or argue about differences and similarities or advantages and disadvantages of these approaches.

2.2.4 Scope of the concept of agile operations

As stated in previous sections – agile operations is not an objective but a necessary means to increase the competitive advantage in times of change and uncertainty (Schönsleben 2000, p. 39). However, to reach agility in operations there is no overall single right way (Bessant et al. 2001, p. 121). Further, literature points out that agile operations is neither a specific method nor a combination of practices (Stelzmann 2011, p. 186). However, agile operations can be seen as capability (Gunasekaran 1998, p. 1223; Christopher and Towill 2001b, p. 236; Stelzmann 2011, p. 186) and is a multidimensional approach (Vázquez-Bustelo et al. 2007, pp. 1305–1306; Bessant et al. 2001, p. 126; Vokurka and Fliedner 1998, p. 170). Therefore, agile operations builds upon knowledge, skills and initiative of people as well as on the availability of information (Gunasekaran 2001, p. 28).

Due to various types of uncertainties and change within the specific business environment of a company, different potential opportunities and disruptions involving any organizational level may encounter agility (Gunasekaran 2001, pp. 27–28; Goldman and Nagel 1993, p. 28). However, the concept of agility is applicable in various settings - e.g. different industries, organizations and corporate functions (Prange and Heracleous 2018, p. 4). In Figure 4 the basic idea of agility as extension to the integrated manufacturing flexibility approach (Wiendahl et al. 2007, p. 785) is shown based on the example of demand volatility. In both, upswing and downswing situations, the concept of agility can positively contribute to optimize the economic situation (Rabitsch and Ramsauer 2015, p. 2).

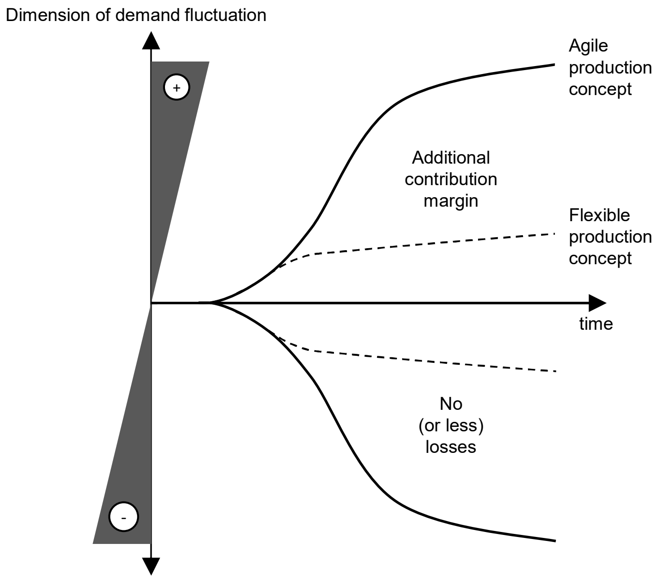

Figure 4: Exemplary impact of agility on demand volatility
(based on Rabitsch and Ramsauer 2015, p. 2) [1, 2]

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[1] the positive impacts of agility are not limited to demand volatility

[2] the impact of agility measures as reaction to upturn and downturn situations does not have to be symmetric

Sull 2009 states that companies can achieve agility through: (1) operational[3] agility – capability to seize opportunities in existing business faster than competitors, (2) portfolio agility – capacity to shift resources to attractive opportunities across business units, and (3) strategic agility – as organizational capacity to identify and seize major opportunities shaping the future of the whole corporation (Sull 2009, pp. 140–142).

Considering the underlying definition of the concept of this thesis, (see 2.2.2.) the above mentioned third type 'strategic agility' is part of the overall strategic work of a company (and not on operations level) and therefore not in focus of this research.

Yusof and Aziz 2008 argue that despite the variance of definitions for the concept of agility (see Table 1) there is an agreement among scholars that agility has two components. First, companies have to 'look inside' their own operations to understand and create responsiveness (Yusof and Aziz 2008, p. 108). This view relates to the 'resource based view' to explain success of organizations based on internal capabilities and sees agility as an 'dynamic capability' (Chiang et al. 2012, p. 51; Vagnoni and Khoddami 2016, p. 626).
Second, companies need to 'look outside' their organization to understand their business environment as well as emerging uncertainties (Yusof and Aziz 2008, p. 108). This market driven view describes the high influence of the external environment driving change and therefore shaping a company's actions (Powell and DiMaggio 1991, p. 49).

However, adaption needs both – internal adjustments to react on external change (Child 1997, p. 69). Strengthening this argument, in literature 'sensing' and 'responding' are defined as two main dimensions of agility (Dove 2001, p. 10 Overby et al. 2006, 121; Nejatian et al. 2018, p. 205; Paek and Lee 2018, p. 891).

Sensing is important and involves the early detection of external change drivers including e.g. competitor's actions, customer demand, technological advancements, legal and political changes (Overby et al. 2006, p. 122). Subsequently, to fully apply agile operations in practice companies must internally identify and reconfigure or integrate needed resources for critical activities to achieve the intended competitive advantage (Yang and Liu 2012, pp. 1024–1026). As stated above, agile operations is a multidimensional approach (Bessant et al. 2001, p. 126) and therefore actions in various operations domains (e.g. production, supply chain) can be necessary to gain agility's full potential (Vagnoni and Khoddami 2016, p. 628). These 'actions' are in literature called e.g. 'agility providers' (e.g. Sharifi and Zhang 2001, p.776), 'measures' (e.g. Gunasekaran 2001, p. 28), 'enablers' (e.g. Yusuf et al. 1999, p. 42) or 'levers' (Rabitsch and Ramsauer 2015, p. 4). Throughout this thesis the terms 'agile operations levers', 'agility levers' or 'levers' are used.

The needed implementation degree of various agility levers might require different approaches and differs across companies and each situation (James-Moore 1997, p. 2). Organizations have to consider to which degree they are capable of configuring specific agility levers to cope with their particular requirements (Brown and Bessant 2003, p. 713). *Zhang and Sharifi 2000* define this

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[3] The term 'operational' "*[...] is the opposite of strategic; it means detailed,localised, short term and day to day.*" (Slack and Lewis 2015, p. 9)

degree of agile operations as ‘agile operations need level’. This need level differs due to company specific factors such as competition, turbulence of the business environment as well as on company internal characteristics. Thus, companies need to determine and reflect on the needed level of agility to achieve the anticipated change to counteract uncertainties as basis for ongoing decision making (Zhang and Sharifi 2000, p. 499).

Further, as stated in the underlying definition for this thesis of agile operations, levers include actions across the whole value chain due to the more far-reaching possibilities of adapting to change (Schurig et al. 2014, p. 957). *Sambamurthy et al. 2003* describe as one aspect of agile operations the ability to “[…] *leverage assets, knowledge, and competencies of suppliers, distributors, contract manufacturers and logistics providers […]*” in order to explore and exploit opportunities (Sambamurthy et al. 2003, p. 246). This leads to an increased effort in establishing and aligning production networks because companies might not be able to provide the needed resources and speed to cope with uncertainties (Gunasekaran 1998, p. 1224).

Figure 5 shows different potential configurations and related questions in order to derive the context specific agility level. Further, as there is no ‘end’ of the journey towards agility (Gunasekaran 2001, p. 27), the continuous measurement of the desired agility level and the current state is needed (Nejatian et al. 2018, p. 202).

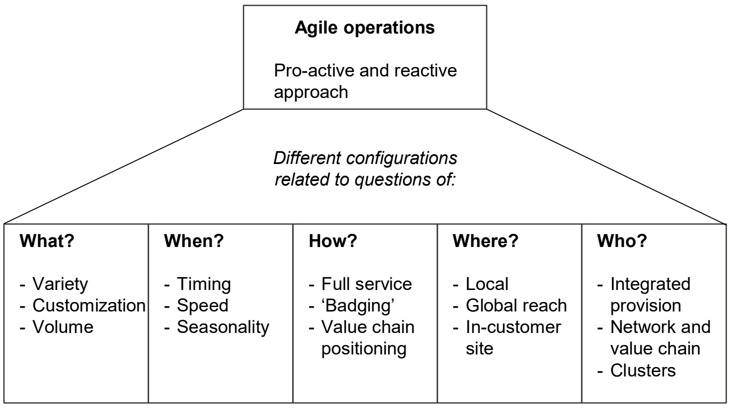

Figure 5: Agility capabilities (based on Brown and Bessant 2003, p. 713)

However, as implementing and maintaining agile operations causes upfront costs, the achievable value when uncertainties emerge must be assessed and reviewed (Rippel et al. 2015, p. 426). Operations management performance objectives in general can be defined as quality (“*[…] consistent conformance to customers’ expectations […]*”), speed (“*[…] time between customer requesting products or services and their receiving time […]*”), dependability (“*[…] delivery/availability of products when they were promised […]*”), flexibility (“*[…] degree to which an operation’s process can change what it does, how it is doing it, or when it is doing it […]*”) and cost (Slack et al. 2010, p. 40). Organizations combine these features to achieve their strategic objectives (Wheelwright 1984, p. 81).

The concept of agile operations addresses all performance objectives of operations management but focuses primarily on speed and flexibility (Slack et al. 2010, p. 47). An empirical investigation performed across “Americas’ Best”[4] manufacturing plants indicates that agile operations represents a higher state of manufacturing performance – except cost efficiency (Narasimhan et al. 2006, p. 453). With agile operations as driving factor in place, a company covers a broader corridor of operation points more efficiently (Deubel 2017, p. 103). Whereas, organizations focusing on a single operation point outperform agile operations driven companies in times of continuous stability (Deubel 2017, p. 103). Figure 6 shows exemplary that difference. Nevertheless, context-specific, different priorities have to be set – e.g. if in markets special emphasis is placed on quality, low costs or short lead-times depending on customers’ value appreciation (Brown and Bessant 2003, p. 725).

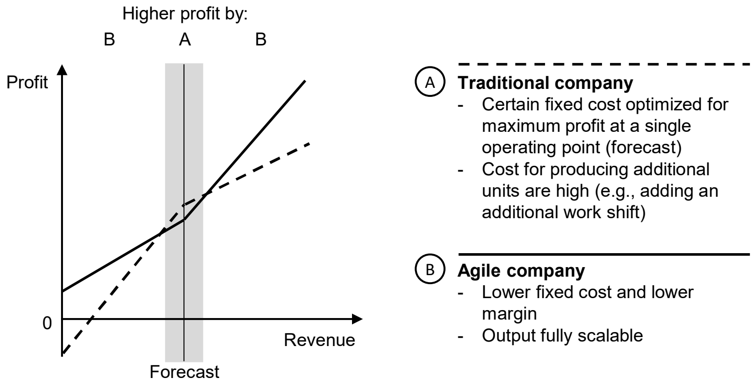

Figure 6: Operating points of agile operations (based on Deubel 2017, p. 103)

Considering the scope and focus of the concept of agile operations - ‘inside’ and ‘outside’ the company; involved organizational functions; different hierarchical levels etc. - it can be stated that it is crucial to take a systems approach towards agile operations (L'Hermitte et al. 2016, pp. 92–93). Practitioners who emphasize a coordinated and cross-functional approach using all company resources to deal with uncertainties also confirm this statement (Barriball et al. 2020, 7; Doheny et al. 2012, p. 3). This research focus in the following on existing conceptual frameworks in literature aiming to define and explain the concept of agility.

2.2.5 Operational frameworks for the concept of agile operations

In order to As stated in the previous section, *“[...] moving to an agile operating model is tough, especially for established companies.”* (Brosseau et al. 2019, 2) Whereas the majority of literature discusses strategies and tools of agile operations, only a few research papers address the conceptualization and development of a holistic concept (Sherehiy et al. 2007, p. 448). *Zhang and Sharifi 2000* presented a first framework consisting of three elements: (1) ‘agility drivers’ – external influences; (2) ‘agility capabilities’ – responsiveness, competency, flexibility and speed; and (3) ‘agility providers’ – practices, methods and tools as basis for the concept of agile operations (Zhang and Sharifi 2000, p. 498). Further, *Sharifi and Zhang 2001* build upon this framework and

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[4] Since 1990 the *IndustryWeek* awards yearly manufacturing plants located in North America (see https://www.industryweek.com/resources/industryweek-best-plants-awards) (2020-10-09)

describe a methodology for its implementation. This methodology builds upon three elementary stages: (1) determination of an organization's agility need level and current agility level; (2) determination of capabilities required to become agile and (3) the identification of tools and practices to improve the current situation. The determination of the agile operations need level is based on following change drivers: marketplace, competition, customer requirements, technology, and social factors. Concerning both, the assessment of the agility need and the current state a tool is introduced by the authors. Further, a tool to identify missing capabilities to achieve agile manufacturing is developed. However, the researchers state that this methodology lacks of validation and needs to be further developed (Sharifi and Zhang 2001, p. 793). Figure 7 shows the methodology and its consisting parts.

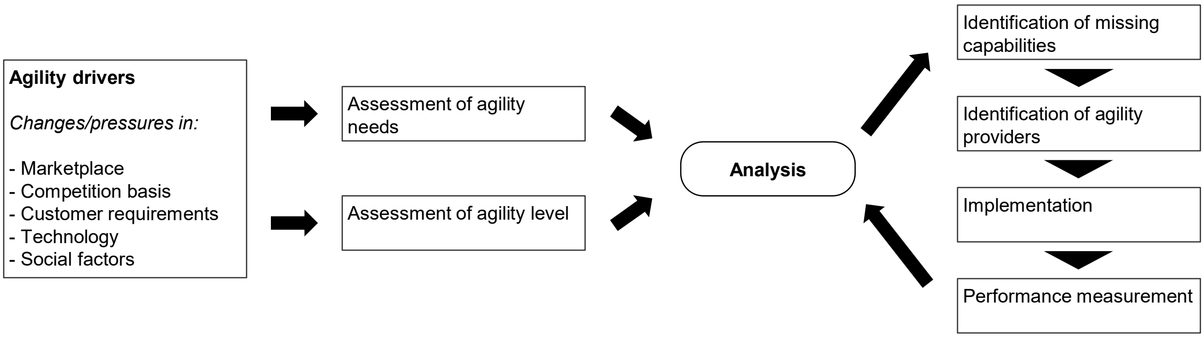


Figure 7: Methodology to achieve agility (based on Zhang and Sharifi 2000, p. 499)

Rabitsch and Ramsauer 2015 strengthen the argument of *Sherehiy et al. 2007* and state that despite the developed frameworks in literature the transition to a practicable approach is not discussed sufficiently. The authors describe first steps towards such a procedure consisting of the building blocks: (1) identification of relevant change drivers; (2) assessment of possible business impact; (3) scenario planning; (4) strategy and target definition; (4) implementation of operational agility levers; (5) define and control triggers; and (6) governance body (Rabitsch and Ramsauer 2015, pp. 5–6). *Rodemann et al. 2019* point out in their literature analysis that the method proposed by Rabitsch and Ramsauer is one of the few ones focusing on production networks and the implementation of agility. Further, they highlight that the proposed agility lever logic enables overall agility through a strategic and an operational orientation. (Rodemann et al. 2019, pp. 565–566)

However, an extensive literature review of 17 frameworks developed within empirical studies throughout the years 1990 to 2018 compares 237 proposed constructs of agility to identify enabler for the implementation of agile operations (Kumar et al. 2019, pp. 163–164). Based on the retrieved results, *Kumar et al. 2019* identify similar constructs and develop a conceptual framework with a base in 'leadership support', consisting of seven pillars and related performance objectives in order to be agile in operations.

Figure 8 shows the proposed framework of *Kumar et al. 2019*.

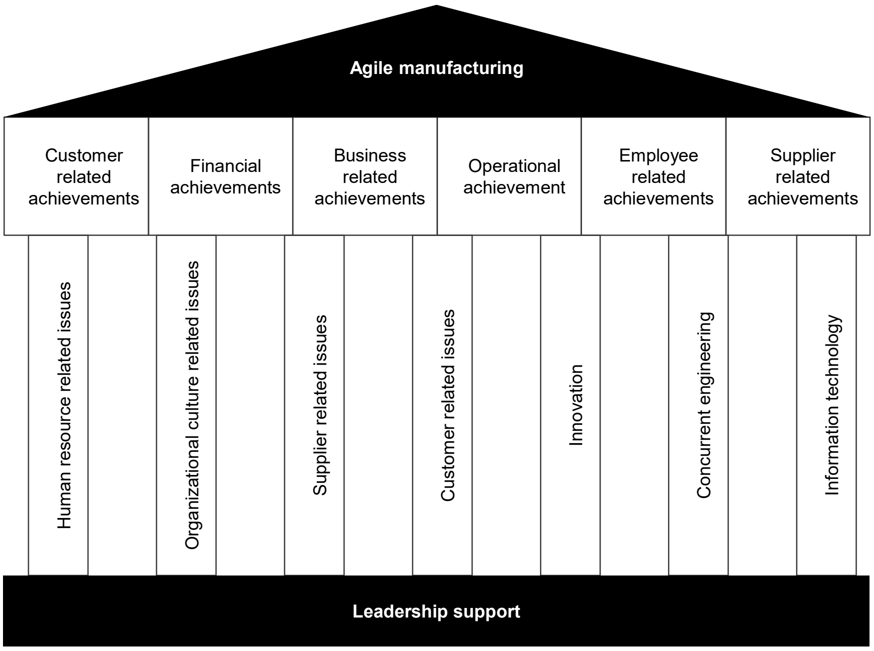


Figure 8: Proposed framework of agile manufacturing (based on Kumar et al. 2019, p. 166)

Nevertheless, similar as stated by *Sherehiy et al. 2007* and *Rabitsch and Ramsauer 2015*, in the point of view of the author of the present research at hand describes the proposed framework of *Kumar et al. 2019* more what an agility concept should contain and not on how to develop an agility system.

In addition, the approach by *Rabitsch and Ramsauer 2015* was further developed throughout the research initiative of 'agile operations' at the Institute of Innovation and Industrial Management at Graz University of Technology. The result, a comprehensive framework of a 'corporate agility system' is described and broken down in to operational elements to achieve agile operations in *Ramsauer et al. 2017.*

Ramsauer et al. 2017 propose an agility system consisting of the two core components agreed upon in literature: (1) 'sensing' – including understanding the external change drivers and monitoring to generate signals; and (2) 'responsiveness' – consisting of governance structure, strategic alignment and operations agility levers as central elements to react quickly. Further, the presented agility system highlights economic success as the overall objective of agile operations. (Ramsauer et al. 2017, p. 21)

Figure 9 presents the proposed framework by *Ramsauer et al. 2017*.

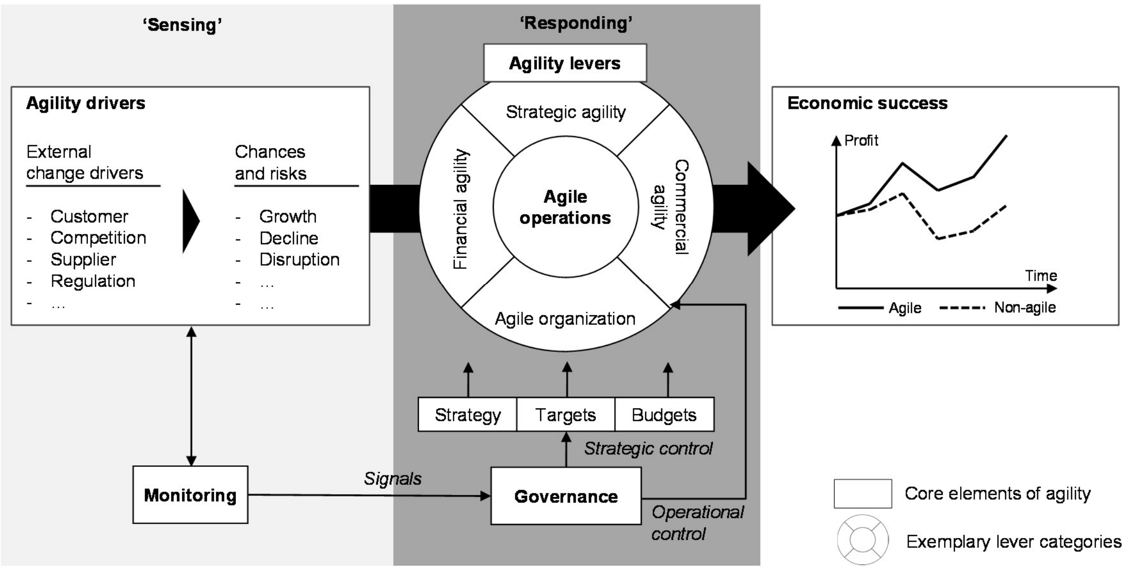


Figure 9: Corporate agility system (adapted on Luczak 2017, p. 21)

The corporate agility system will be used as basis in the further course of this work due to the shared underlying understanding of agile operations by *Luczak 2017* and the present thesis at hand as well as the operational and practical orientation of the chosen framework.

Further, as the focus of this research is explicitly on how to cope with uncertainty in operations, topics with a focus on corporate strategy, organizational development, corporate culture, marketing and financial aspects are only peripherally addressed.

2.2.6 Core elements of the agile operations framework

This section describes the core elements of the two components 'sensing' and 'responding' of agile operations in more detail. The objective of this section is to provide a solid base for the empirical work of this thesis.

Agility drivers

Several frameworks of how to address uncertainties are available in international standards (e.g. "Risk management: principles and guidelines" by the International Organization for Standardization - ISO 31000:2009). Risk management approaches typically contain following steps: (1) risk assessment; (2) tolerability/acceptability judgment; (3) management of risk and (4) risk communication (Grøtan and Paltrinieri 2016, pp. 246–247). However, consulted literature points out that risk management in practice focuses especially on the downside of risk (Sommerfeld 2015, p. 49). Further, risk management is in practice more concerned with financial and operational risk and seems not be applicable for managing uncertainties in a greater context (Kaplan and Mikes 2012, p. 51).

Managers, however, understand, deal and act due to uncertainties according to *Zsidisin 2003* very often as the following: (1) what is the downside/upside?; (2) what is the magnitude of potential losses?; (3) what are we going to do?; and (4) managers perceive risk and uncertainties not as concept that is "*[…] captured with a single number.*" (Zsidisin 2003, p. 218) However, uncertainties are driving forces for organizations and subsequently managers must learn how to cope with them (Narain et al. 2000, p. 204).

Gass and Fu 2013 describe five levels of uncertainty with different aspects of available knowledge (see Figure 10). 'Level 1' is a state where future is not absolutely certain anymore but impacts can be estimated with sensitivities. 'Level 2' describes situations where future outcomes can be modeled via statistics. 'Level 3' refers to uncertainties about alternative futures still possible to rank by the probability of occurrence. 'Level 4' uncertainties are identifiable but can no longer be prioritized. 'Level 5' uncertainties, labelled as 'true' uncertainties by *Knight 1921*, are situations where no knowledge about future developments exist (Gass and Fu 2013, pp. 396–397).

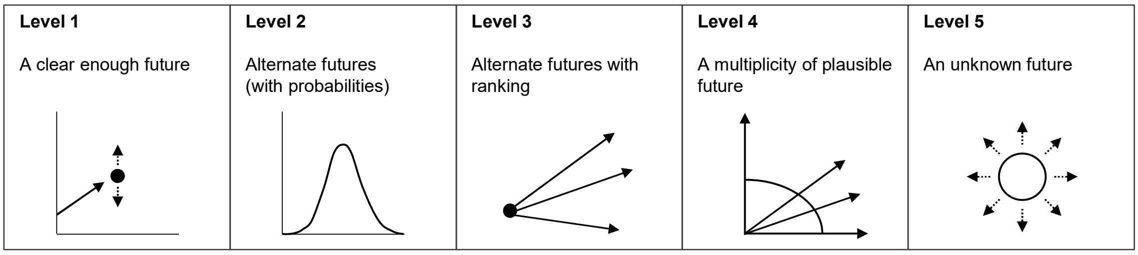


Figure 10: Types of uncertainty (Gass and Fu 2013, p. 396)

As previously mentioned, today our world experiences an increasingly rate of uncertainties (Sheffi 2015, p. 354). Closely related with the growing perception of uncertainties are unknown cause-effect interrelationships, unstable business enivornments; as well as uncertain future developments causing disturbance to operations (Kremsmayr 2017, pp. 47–52).

Categorizing uncertainties systematically provides an approach to cope but there is no 'one size fits all' solution (Cheese 2016, pp. 323–324). However, Table 2 lists exemplary types of uncertainties based on literature and a categorization approach by the area of origin of uncertainties proposed by *Kremsmayr 2017*.

Table 2: Exemplary types of uncertainties (based on: Zsidisin 2003, p. 221; Wu et al. 2006, p. 354; Zanjirchi et al. 2017, p. 696; Kremsmayr 2017, p. 55)

Area of origin		**Exemplary factors affecting the occurrence**	**Examples of uncertainties**
Macro level	Uncertainty due to changing influencing factors in the global environment	Natural disasters	Earthquake Volcano Flood
		Political / economical stability	Economic downturn New government Rules/Regulation changes
		Security / man-made uncertainties	Maritime pirate attack IT / Internet security Third party labor strike
Micro level	Uncertainty due to developments and trends in individual industries and markets	Market characteristics	Market growth Sudden shoot-up of demand Mismatch predicted vs. actual demand
		Supplier related uncertainties	Input cost volatility Quality of raw material Supplier availability Supplier market strength
		Customer related uncertainties	Loss of contracts Legal claims by customers Loss of customer reputation
Company level	Uncertainties due to the immediate/internal environment of the company	Production	Quality Cost Production process
		Human resources	Legal claims by employees Lack of access to qualified staff Labor strike
		Accidents	Fire accidents Accidents in Transportation Occupational accidents

Sheffi 2005 states that despite the differences in severity and duration, uncertainties leading to disruptions have characteristic stages. Figure 11 shows exemplary these stages from 'preparation' and 'first response' to the 'long-term impact'. The graph depicts a fictional performance of a company (e.g. sales, production rate, etc.) throughout a disruption. (Sheffi 2005, p. 65)

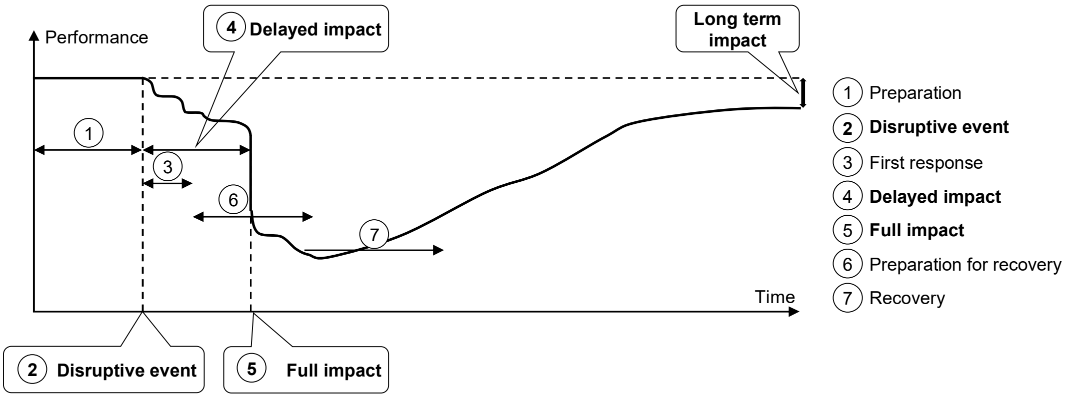
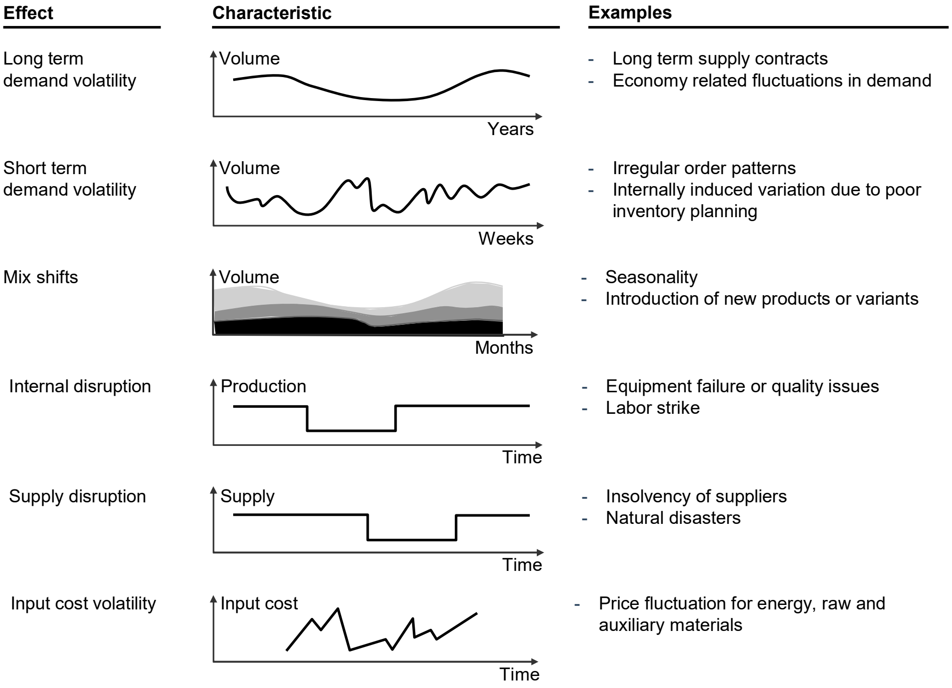


Figure 11: Profile of a disruption (exemplary) (Sheffi 2005, p. 65)

Further, *Alicke et al. 2014* and *Kremsmayr 2017* describe six typical effects of uncertainties on operations (see Figure 12). In addition, *Alicke et al. 2014* from a practitioner's point of view add 'safety and operational risks' as seventh source of uncertainty with an impact on operations. This considers unforeseen equipment- and process failures (Alicke et al. 2014, pp. 37–38). The concept of agile operations as seen by this research study aims to cope especially with the presented effects on operations in following Figure 12 published by *Kremsmayr 2017*.



Effect	Characteristic	Examples
Long term demand volatility	Volume Years	- Long term supply contracts - Economy related fluctuations in demand
Short term demand volatility	Volume Weeks	- Irregular order patterns - Internally induced variation due to poor inventory planning
Mix shifts	Volume Months	- Seasonality - Introduction of new products or variants
Internal disruption	Production Time	- Equipment failure or quality issues - Labor strike
Supply disruption	Supply Time	- Insolvency of suppliers - Natural disasters
Input cost volatility	Input cost Time	- Price fluctuation for energy, raw and auxiliary materials

Figure 12: Effect and characteristics of the impact of uncertainties on operations
(Kremsmayr 2017, p. 55)

Monitoring

It can be stated that "[…] *faster, better and proactive decision making is the key driver of strategic value.*" (Hagen et al. 2013, p. 4) The ability to early identify uncertainties, whether problems nor opportunities, is the basis to react quickly and subsequently a requirement for achieving a competitive advantage (Mukherjee 2009, p. 1). Strengthening this argument, *Teece et al. 1997* report that 'winners' in global competition are organizations able to quickly react paired with effective decision-making (Teece et al. 1997, p. 515). To be able to react quickly and for fast decision-making a higher amount of information is needed (Eisenhardt 1989, p. 544). Monitoring in the context of the corporate agility system is defined by *Heldmann 2018* as *"[…] the interface to the volatile business environment […]"* enabling the early detection of relevant uncertainties (Heldmann 2018, p. 15).

However, increasing complexity in business environments calls for a higher organizational perception in order to obtain information, to build knowledge and to manage uncertainties in the following (Nobre 2011, p. 436). Due to the importance of reacting to external developments, virtually all organizations conduct in some form monitoring activities (Wilson 2004, p. 208). Otherwise, organizations might tumble from crisis to crisis, whether large or small

(Mukherjee 2009, p. 1). Therefore, monitoring of external developments is an essential building block of the concept of agile operations (Heldmann 2018, p. 107).

Figure 13 shows exemplary the mechanics of how monitoring and agile operations work together in a case of demand upswing. The timely recognition of the early warning signal (A); a short response time (B); the speed of the reallocation of resources (C); as well as the impact and impact duration (D,E) of the reaction (implemented agility levers) enable organizations to gain competitive advantages in times of change (Heldmann 2017, pp. 163–164). The response time (B) includes perception, decision-making, realization and the planning time but it is obvious that the earlier an uncertainty and its implications are recognized the sooner it can be reacted to (Hernández Morales 2003, p. 49).

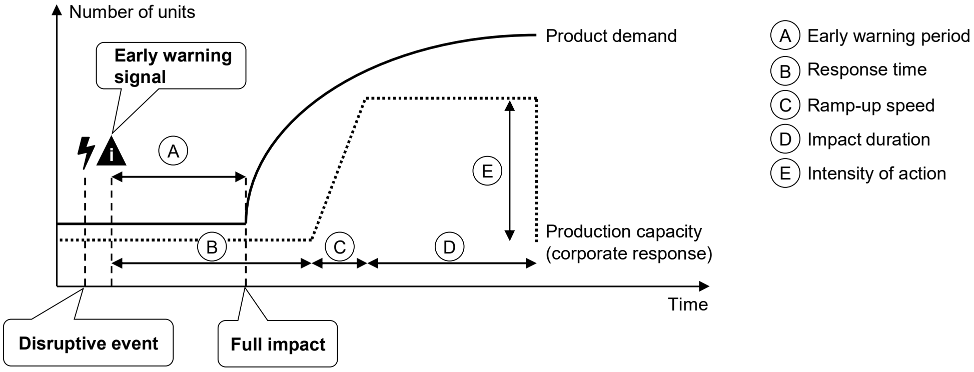


Figure 13: Mechanics of monitoring and the concept of agility (based on Heldmann 2017, p. 167)

Further, *Heldmann 2017* describes two types of monitoring: (1) signal based monitoring of measurable information for operations control, and (2) information based monitoring where relevant information needs to be interpreted for strategic control. In both cases selecting and placing of sensors is necessary to obtain quantitative as well as qualitative input information. The author points out that both types of monitoring are not strictly separated. However, in practice, five typical monitoring fields are in the scope of most company activities: (1) input factors/raw material; (2) suppliers; (3) technologies; (4) market, and (5) competition. (Heldmann 2017, pp. 163–174)

Monitoring in a strict meaning is concerned with describing ‘what is’ (Wilson 2004, p. 208) whereas companies should integrate scenario processes to strengthen the ‘sensing’ mechanism of the organization (Vagnoni and Khoddami 2016, pp. 631–632). Scenario planning explores not only single events but rather interactions, combinations and the evolution of uncertainties (van der Heijden 2005, p. 117). The derived scenarios serve as a frame for monitoring activities (Wilson 2004, p. 208). For detailed information about scenario planning see e.g. *Schwartz 1996* and *van der Heijden 2005.*

Such a scenario based approach highlights that management judgement is important for an effective implementation of monitoring (Yusof and Aziz 2008, pp. 108–109). Therefore, a monitoring system further requires a communication procedure to deliver the gained information timely and in an adequate format (Laudon and Laudon 2018, pp. 47–49). *Teece 2007* points out, that interpretation and assessment of received signals is necessary to decide upon measures whether it is about which technology is being pursued further or where the organization wants to position itself in relation to suppliers, customers or competitors. However, due to uncertainty, often conjectures evolve and these working hypotheses are constantly updated, and actions are taken when needed (Teece 2007, pp. 1322–1323).

Sheffi 2015 describes the importance of monitoring and the related processes using the case of the company Cisco and the earthquake in 2011 in Japan. The monitoring process at Cisco runs 24/7 and combines information tracking with an escalation process. The monitoring activities detected and the process behind escalated the earthquake and possible implications in less than 60 minutes from the time of the earthquake to the senior management (Sheffi 2015, p. 326). Therefore, strategic and operational control build upon monitoring activities (Heldmann 2018, p. 15).

Strategic alignment

Sensing an opportunity or a disruption needs appropriate countermeasures in form of resource reallocation (e.g. new products, new services, adapted processes) in order to adapt the corporate system (Teece 2007, pp. 1326–1329). The corporate ability to quickly react on uncertainties and therefore adapt to resulting effects on operation is as well a strategic challenge (Schönsleben 2009, p. 383). To compete in today's business environment corporate strategy and operations strategy need to be aligned (Brown 2001, p. 44). As stated in 2.2.1, operations strategy is linked to the corporate strategy and is the strategic perspective dealing with long-term decisions and actions of how resources and processes in operations are managed (Slack and Lewis 2015, p. 9). Agility is enabled by an operations strategy in place to integrate know-how, skills, processes, technologies and cooperation across value networks (Brown and Bessant 2003, p. 708).

Agility still builds upon classic operations management capabilities (Brown and Bessant 2003, p. 710) while synchronizing external developments with internal processes (Wiraeus and Creelman 2019, p. 13). The impact of agility in operations on the corporate ability to adapt depends on the strategic alignment of agility driven actions (Meredith and Francis 2000, p. 138; Bessant et al. 2001, pp. 125–126). Alignment is hereby understood similar to 'congruence' and is defined as "*[…] the degree to which the needs, demands, goals, objectives, and/or structures of one component are consistent with the needs, demands, goals, objectives, and/or structures of another component.*" (Nadler and Tushman 1980, p. 45)

Without such a strategic framework, organizations are just able to react and not to pro-actively prepare for change (Prahalad 2009). Strengthening this argument, alignment is seen as key factor and basis for the concept of agility (Shin et al. 2015, pp. 185–186). Central for agility is the fast and effective deployment of strategy by breaking down main strategic objectives (Gunasekaran 2001, pp. 115–121) paired with responsiveness in operation to realize competitive advantages from the strategic framework (Yusuf et al. 1999, p. 39).

Therefore, as introduced by *Teece 2007* decision-makers must decide under uncertainty how to stay competitive by considering several trajectories of the future and managing necessary investments. Thus, agility might need upfront investments and even several parallel investment paths emerge. In consequence, a common reason for organizations not seizing a spotted opportunity is failing in invest. (Teece 2007, pp. 1326–1329)

However, steps to develop an approach aligned with strategy are in general (1) current situation analysis, (2) identification of the need, (3) development of solution variants, and (4) processes for solution selection (Wohinz 2003, p. 74). Alike, *Sharifi and Zhang 2001* introduced a conceptual model to align agility to corporate strategy and to support strategy formulation. The three main steps are: (1) analysis of the current agility level; (2) determination of agility needs; and (3) identification of needed levers to close the gap (Sharifi and Zhang 2001, p. 775). Figure 14 shows the conceptual model to support strategy formulation considering agility.

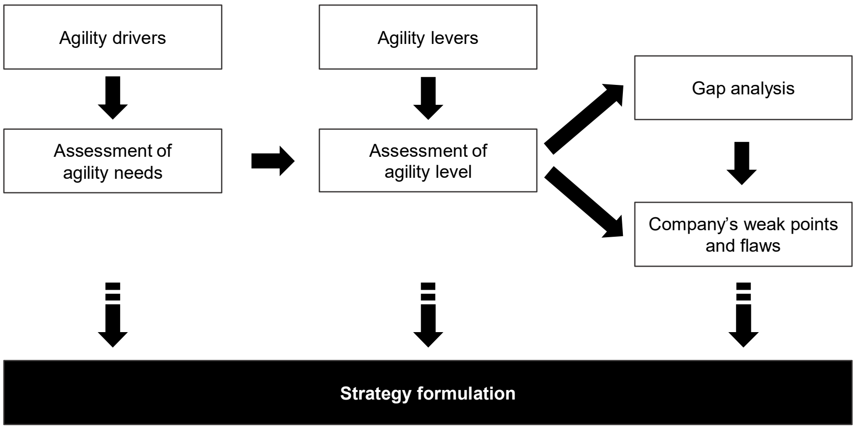


Figure 14: Assessment for agility (based on Zhang and Sharifi 2000, p. 500)

Hence, there is a need for suitable metrics to measure the gap between current and the context-driven need of agility levels to derive suitable countermeasures (Nejatian et al. 2018, p. 202). These metrics enable as well the coordination of agility activities (Gunasekaran 2001, pp. 115–121). However, the multi-dimensionality of agility causes that it cannot be measured universally similar to the integrated concept of flexibility (Narain et al. 2000, 2000, p. 206; Hernández Morales 2003, p. 83). Further, depending on the business environment performance objectives like quality, costs, product variety or lead-time have to be treated differently (Naylor and Keogh 1999, p. 108; Bessant et al. 2001, pp. 125–126). Additional, the impact of agility measures and subsequently the agility level of an organization is varying for different scenario alternatives and the point in time (Dove 1994, p. 5; Sharp et al. 1999, p. 162). Therefore it is stated in literature that it is hard to employ meaningful and comprehensive metrics of agility (Yang and Liu 2012, p. 1026). Still various scholars have proposed approaches to measure agility (Sherehiy et al. 2007, p. 449). *Metes et al. 1998* introduced a Balanced Scorecard[5] approach to measure domains of agility. *Ren et al. 2000* proposed an index approach based on the work of *Goldman et al. 1995* and *Yusuf et al. 1999*. *Cheng et al. 2015* and *Yang and Li 2002* propose a fuzzy logic evaluation approach.

Concerning detailed Information about measurement methods for agility this research refers to the work by *Shaarabh 2014* who performed a review on different methods to measure agility.

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[5] The Balanced Scorecard is a management approach to clearly visualize corporate mission and strategy from four perspectives: financial perspective, internal perspective, customer perspective and learning and growth perspective (Kaplan et al. 1997, pp. 140–145).

Based on a continuous assessment and gap analysis between desired and needed agility level suitable countermeasures - hereinafter referred as 'agile operations levers' - need to be derived (Sharifi and Zhang 2001, p. 775). Due to its importance, more details concerning these agile operations levers can be found in the following subchapter 'agile operations levers'.

Agile operations levers

As stated by *Sambamurthy et al. 2003,* companies react to competitor's actions and therefore competitive advantage is very often only short-term. To regain advantage companies have to constantly readjust with appropriate actions. Hence, pro-active preparation and more variety in such actions will result in a better market position. (Sambamurthy et al. 2003, p. 241) Such actions concerning agility are enabled by agility levers. The term 'lever' is defined as a measure "*[...] of a company which can be modified in order to actively respond to a specific undesirable situation.*" (Schmitt et al. 2013, p.246)

To gain competitive advantages several factors across the operations domain (e.g. employee skills, inventory, quality, production technologies) need to be leveraged in parallel (Brown and Bessant 2003, p. 725). In general, relating to Figure 13, agile operations levers or their combination influence the response time, the speed of reallocation of resources, the duration time and/or the impact intensity on operations (Heldmann et al. 2015, p. 37). Moreover, as mentioned above, agility is driven by constant change in business environments. Therefore, agile operations levers need to be defined context specific by companies on an individual basis (Goldman et al. 1995, pp. 72–74; Gunasekaran 2001, pp. 27–28; Sheffi 2015, p. 352; Zhang and Sharifi 2000, p. 497). To identify operational measures to enhance agility requires out-of-the-box thinking and to a certain degree the un-learning of existing rules (Roth 1996, p. 31).

To support the individual task of defining agile operations levers scholars defined several classification categories in order to structure agility levers. For example, *Schurig 2016* structures levers in two categories, namely in internal focus (operational, labor, assets) and external focus (supplier) (Schurig 2016, p. 110). Based on literature *Swafford et al. 2006a* structures agility measures in procurement/sourcing, manufacturing and distribution/logistics (Swafford et al. 2006a, p. 121). *Rodemann et al. 2019* proposes production network, supply chain and resources as well as coordination efforts concerning organizational structures, coopetition and cross-domain collaboration as agility design dimensions (Rodemann et al. 2019, p. 567). From a practitioners point of view *Alicke et al. 2014* define the functions product development, purchasing, manufacturing, supply chain and sales and marketing as categories to structure relevant agility levers (Alicke et al. 2014, p. 40). *Luczak 2017* defines the categories of agility levers as follows: work organization, production assets, procurement, logistics (inbound and outbound), production network and product design (Luczak 2017, p. 21). Table 3 shows exemplary agility levers summarized by *Pointner 2017*. Enablers and agile operations levers can be found in scientific literature (e.g. Pointner 2018, pp. 189–193, Vázquez-Bustelo et al. 2007, p. 1309; Sharp 1999, p.161) and in reports published by practitioners (e.g. Beardshow et al. 2013, p.4; Manyka et al. 2020).

Table 3: Exemplary list of agile operations levers (Pointner 2017, pp. 204–222)

Category	Enablers / agile operations levers to react on change
Work organization	High performing people under uncertainty (e.g. taskforce)
	Temporary workers (e.g. freelancer, extension - time to hire/fire)
	Flexible employment contracts for production employees
Production assets	Qualification of volume products at two or more production sites
	New business models with existing equipment (e.g. pay-on-production, acting as contract manufacturer or leasing of own equipment)
	Strong focus on agile production technologies (e.g. 3D printing)
Procurement	Agile end-to-end supply chain: transparency about and active management of end-to-end supply chain from tier 1 to tier n supplier
	Establishing strategic partnerships with selected suppliers. Price advantages and preferred customer status in times of crisis help companies to avoid supply interruptions
	Multi-sourcing strategies to protect against supplier failures are in place
Logistics	Fast reaction in logistics by changing means of transport (e.g. truck, ship, train, plane)
	Decentralized warehousing strategy to ensure short delivery times due to proximity to the customer/supplier to reach.
	Targeted outsourcing of logistics services
Production network	Decentralized organizational units and processes in the production network to be able to react faster
	Standardized processes, production facilities and employee qualification as a basis for a shifting of customer orders within the production network.
	Dynamic distribution of sales orders in a production network, to react to fluctuations in demand, changes in variants, and delivery disruptions.
Product design	Modular product design with defined interfaces supports the rapid adaptation to variants
	Consideration of raw material changes in product design (Design-for-Switchability)
	Product design in order to realize late product differentiation in the production process

Further, digitalization can be seen as strong enabler for the concept of agility due to the possibilities of data processing, connectivity, analytics, intelligence, human-machine interaction or technologies to convert digital models to physical products (Pointner 2017, pp. 226–229).

As mentioned above, decision makers have to consider different future scenarios and therefore different lever as well as lever combinations must be considered simultaneously (Teece 2007, pp. 1322–1323). To identify a suitable application of different levers/lever combinations for a specific scenario requires an evaluation of these measures considering the overall business situation (Nabass and Abdallah 2019, p. 661). Following four characteristics of levers serve as basis for decision-making: (1) volume benefit; (2) time-related aspects (implementation time and effective time-period); (3) cost-related aspects (reconfiguration costs and operating costs); and (4) dependencies of levers/lever combinations (Pointner 2018, pp. 73–89). *Eppinger and Browning 2012* highlight, that especially interactions of levers are crucial for the overall result. The input certain levers require (e.g. investment, ressources) and how they act in combination with other levers define the value-add. Interactions include following four relationships of levers: (1) 'sequential dependability' where lever B needs the output of lever A; (2) 'parallel' where levers A and B are independent; (3) 'coupled' where lever A and B are interdependent; and (4) 'conditional' where either lever A or lever B can be applied (Eppinger and Browning 2012, pp. 133–134). However, the realization or activation of prepared agility levers needs a procedure to be followed due to the necessity of an thoroughly understanding of the overall situation by decision-makers (Nabass and Abdallah 2019, p. 661).

There exist further literature on how to configure the agility need level. *Schurig 2016* introduces a methodology to evaluate the agility of a production network using a simulation model and a stress test approach. *Pointner 2018* introduces a guiding procedure to assess different configurations of options to react on demand upswings in production.

Governance

Besides know-how and resources reacting on perceived change requires processes and management infrastructure (Williams et al. 2013b, p. 7). The concept of agility requires strategy execution and a constant coordination effort across the organization due to its multi-dimensionality and its focus on seizing opportunities (Sull et al. 2015, pp. 61–62). In addition *Meredith and Francis 2000* state that in order to be successful agility requires the management of complexity (Meredith and Francis, 2000, p. 140). Further, *Yusuf et al. 1999* state that the concept of agility *"[...] requires massive structural and infrastructural changes."* (Yusuf et al. 1999, p. 36). The broad context of changes and the frequency of decisions to be taken to obtain a competitive advantage requires a governance function (Aghina et al. 2015, p. 8).

Governance is defined as "*[...] the system by which companies are directed and controlled.*" (Cadbury 1996, p. 14). Corporate governance in general deals with defining corporate strategic aims, providing leadership, controlling of management, and reporting to shareholders (Cadbury 1996, p. 14). Therefore, the objective of governance is to coordinate agility activities across stakeholders and serves as central hub for information throughout the value-add processes (Rabitsch and Ramsauer, 2015, p. 6).

Hönl 2017 states concerning the corporate agility system that the governance module of the corporate agility system must be distinguished from the corporate governance. First, it does not mean that the entire control logic of the company must be designed for agility. Rather, the agility building blocks must be able to be integrated into existing structures such as the committee landscape and decision-making processes. Second, the aim is not to make the management model itself more agile. Rather, the control model for agility must be described in terms of how the requirements and design options of the agile enterprise system are to be filled with life (Hönl 2017, p. 240). The integration in the existing corporate body is mainly specific to each organization (Zhang and Sharifi 2000, p. 497). However, the governance module incorporates a strategic and operational control function within the corporate agility system (see Figure 9).

Concerning strategic alignment and control, it is important to match the rate of external change with the internal strategy process (Kennerley and Neely 2003, p. 218). Further, the activities need to be monitored and initial planning assumptions need to be scrutinized on a regular basis to ensure their relevance (Sull, 2009b, pp. 151–152). Performance management is linked to strategic control and describes the "*[...] process of quantifying the efficiency and effectiveness of action.*" (Neely et al. 1995, p. 80)

According to *Hönl 2017*, the operational control element of governance coordinates, ensures the necessary exchange of information, and supports cross-functional coordination. It is thus the link between the various agility modules across the corporate functions. An operational structure must be created so that activities aligned with strategy based on external changes (monitoring) can be implemented as concrete actions (agile operations levers). (Hönl 2017, p. 248)
Figure 15 shows such a workflow schematically as published by *Barriball et al. 2020*.

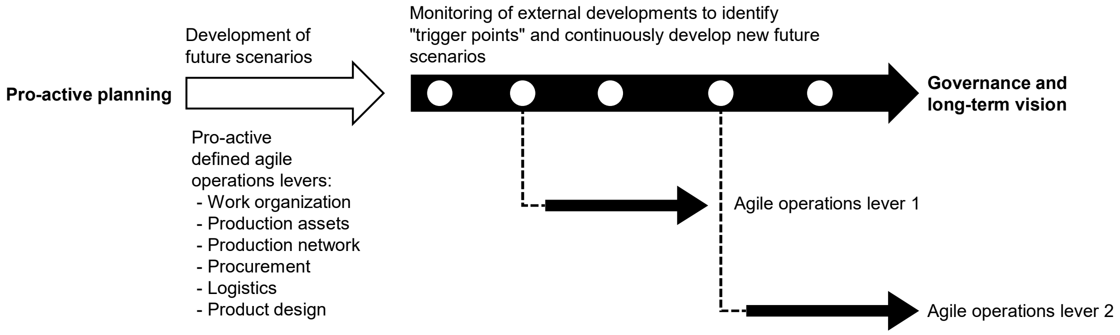

Figure 15: Agile operations work flow (adapted from Barriball et al. 2020, p. 7)

Hönl 2017 describes that even if there is no generally valid blueprint for an agility governance body four important design dimension can be highlighted: (1) roles and responsibilities; (2) processes to orchestrate the agility system; (3) organizational structure; and (4) culture and behavior. In terms of roles and responsibilities, it is particularly important to define which roles are anchored in the management model and that responsibilities for what and to what extent are defined. Further, the distinction between day-to-day business and tasks of the agility concept is necessary. (Hönl, 2017 p.248-249)

From a practitioners point of view *Barriball et al. 2020* propose a three level network of responsibilities: (1) ‘plan-ahead responsibility’ for the constant development of scenarios; (2) ‘design responsibility’ to create agility levers; and (3) ‘implementation responsibility’ to coordinate and execute change (Barriball et al. 2020, p. 7). However, depending on the importance of agility in the organization, roles and responsibilities of the governance function can range from pure coordination to active intervention in daily operations (Hönl 2017, p.249).

Concerning processes to orchestrate activities, the focus is on the continuous identification of needs for action as well as a fast and effective decision for the implementation of suitable levers (Hönl 2017, p. 249). As agility is a pro-active approach, pre-defined implementation processes for developed scenarios are key to quickly seize opportunities (Nabass and Abdallah 2019, p. 661). *Hopman 2005* proposes a so-called ‘playbook’ to enable the pro-active definition of tactics to respond future scenarios. This approach comes from the sports sector where players have to act under high stress and time pressure. (Hopman 2005, p. 177)
The definition of agility playbooks that represent a bundle of coordinated agility levers to react quickly to a defined scenario is also stressed by *Luczak 2017*.

Related enablers of agile operations: organization, corporate culture and behavior

The corporate agility system (see Figure 9) as the underlying framework of this research points out that 'organization and culture' can be seen as enabler for agility (Luczak 2017, p. 21). The topic of 'agile organization' is broadly discussed in literature and includes the topic of 'culture and mindset' (e.g. *Holbeche 2015; Denning 2016; Naslund and Kale 2020*). This research focuses solely on agile operations and therefore refers to the ongoing discussion in literature concerning 'agile organization'. Table 4 lists basic principles to give an outlook on agile organization and culture and behavior research.

Table 4: Principles of agile organization and agile culture and behavior (based on Dubey and Gunasekaran 2015, p. 2149)

Agile organization	Flat hierarchical organization
	Minimal formal (functional) authority
	Minimal routinization and standardization
	Informal coordination and empowerment
Agile culture and behavior	Innovation and risk taking
	Attention to detail
	Focus on people and individuals
	Stability

2.2.7 Agile operations and competence development

Operations improvements and sustaining change within organizations depend on engagement and further development of employees capabilities (e.g. Kotter 1996, pp. 101–102). Several well-known operations improvement approaches like lean, six sigma, total quality management or business process reengineering stress trainings and education as necessary basis for their implementation (Mi Dahlgaard-Park and Dahlgaard 2006, pp. 273–274; Chiarini 2011, p. 332). According to *Brosseau et al. 2019* the same applies to the concept of agility since "*...moving to an agile operating model is tough, especially for established companies*" (Brosseau et al. 2019, 2). In this context, literature points out that capabilities of employees and their empowerment are the key resources when it comes to an agile transformation despite the availability of advanced manufacturing systems (Gunasekaran et al. 2019, p. 9). However, literature further states that dealing with the implementation of agile operations is "*[...] first and foremost a responsibility of management.*" (Wiendahl et al. 2015, p. 109) Hence, a management approach for the implementation of agility due to the corporate wide system change in combination with an ability to see agility as success factor for long term competitive advantage is crucial (Williams et al. 2013a, p. 4). Therefore, one key aspect to become agile is to leverage responsible employees and managers' knowledge and skills (Dove 1994, pp. 7–8; Plonka 1997, pp. 13–15; Gunasekaran et al. 2019, p. 5162).

Engagement and the ability of the top-management to motivate and provide training opportunities for their employees are further pre-requisites for the successful implementation of agile operations (Prange and Heracleous 2018, p. 4; Yusuf et al. 1999, p. 39). Thus, "*[...] to achieve agility, managers would be well advised to design and effectively implement appropriate policies and* *practices for learning and training."* (Muduli 2017, p. 54) Yet, today's curricula in management education focus still on stability rather than on uncertainty (Hall and Rowland 2016, p. 952).

To the author of this research there is at the present no related research known addressing the issue of agile operations trainings to design an agile operations system. However, in their research work with the intent to analyze international research and development programs at the manufacturing sector *Putnik 2012 et al.* states that agile operations should be implemented in education (Putnik et al. 2012, p. 279).

Meuse et al. 2010 state that learning agility is independent from the application field (e.g. different industries). Further, the author describes the case of U.S. military, which identified the need of agility for their soldiers in order to navigate in war situations. Therefore, first insights concerning learning and agility might be transferred from military's research or emergency management. *Meuse et al.* conclude that for managers it is essential to invest time to learn how to cope with uncertainty. (Meuse et al. 2010, pp. 120–123).

Chinn et al. 2019 describe the case of the British army applying agility in its design of strategy and policy. The objective was to enhance operational effectiveness. Agility resulted in three benefits: (1) increasing productivity; (2) decentralized decision-making; and (3) better adaption to respond changing environments. However, the British army points out that especially training sessions enabled adoption and the improvement of their approach (Chinn et al. 2019, 2–7). Looking into the case of the U.S. military *Gehler 2005* concludes that training to support the development of agile-capabilities needs to be dynamic and experienced-based in order to gain opportunities in applying lessons, receive feedback and then to apply gained knowledge again. Applied training means of the introduced approach are case studies, field trips and simulations. (Gehler 2005, p. 4)

Mendonca and Fiedrich 2006 point out in their research 'Training for improvisation in emergency management' the necessity of proactive training activities. The authors identify four overall objectives for increasing managing uncertainties in emergency situations: (1) when to depart from standard-procedures; (2) how to carry out and operationalize new procedures; (3) communication with decision-makers; and (4) conclusions about the present and probable future scenarios. (Mendonca and Fiedrich 2006, pp. 350–351)

These objectives seem to partially overlap with central activities of agile operations work flow (see e.g. Barriball et al. 2020, 7; (Zhang and Sharifi 2000, p. 499). Concerning training for emergency management *Mendonca and Fiedrich 2006* propose especially the application of a suitable learning environment with high authenticity and the possibility to manipulate design variables like the magnitude or dynamism of simulated crisis (Mendonca and Fiedrich 2006, pp. 353–357).

2.2.8 Summary: The concept of agile operations

Based on the literature discussed and according to the specific requirements of this research agile operations is understood throughout this work as the:

“[…] capability of a company to prepare proactively for uncertainties and react quickly to changes to optimize the economic situation by leveraging the entire production network.” (Schurig 2016, p. 64)

The concept of agility is a multidimensional approach and therefore requires measures in several operations domains (e.g. production, logistics, purchasing) to gain its full potential. Further, companies not only have to adapt internally to change but also to include more far-reaching possibilities enabled by measures across the value network. The concept of agility is not limited to a certain industry.

In accordance with the literature consulted, this work incorporates two main pillars of agility: (1) ‘sensing’ in order to understand external change drivers and the execution of monitoring to generate signals; and (2) ‘responsiveness’ to react on perceived signals and to quickly adapt in order to gain competitive advantages due to change. While the advantage of ‘sensing’ external uncertainties in turbulent times is obvious, a deep market understanding constitutes likewise in stable times a competitive advantage. The required responsiveness depends on company specific factors (e.g. competition, turbulence, industry). Agile operations levers describe potential measures to reach the company individual agility need level and highlight the pro-activeness of the agile operations concept.

Considering the scope of agile operations and involved corporate functions a systems approach to develop a holistic concept of agility is needed. This research considers the ‘corporate agility system’ (see Figure 9, Luczak 2017, p.31) as underlying framework for the empirical part. This framework of agile operations is broken down into five core elements (see section 2.2.6): (1) agility drivers; (2) monitoring; (3) strategic alignment; (4) agile operations levers; and (5) governance. Whereas ‘agility drivers’ and ‘monitoring’ relate to the pillar of ‘sensing’ the other three core elements contribute to a corporate’s responsiveness.

The in-depth analysis of agility drivers is inevitable to understand the business environment. Within this element, the basis for the assessment of the necessary agility need level emerges. Monitoring activities enable the early identification of uncertainties (challenges and opportunities) and are the basis to respond quickly in order to gain a competitive advantage. Monitoring aims to obtain information, gain knowledge in order to manage complex and uncertain situations. Strategic alignment is a necessary means as the integration of knowledge, skills, processes and technologies in combination with value chain cooperation enables agile operations. Without an alignment across all corporate functions, organizations are not able to pro-actively thrive on change. To maintain a competitive advantage a continuous, fast and effective deployment of strategy is key. Agile operations levers need to be defined to constantly adjust appropriate actions. The basis for the pro-active preparation of these context specific levers is the individual agility need level of each company. Governance coordinates activities across all stakeholders and serves as information provider concerning core agile operations elements within an organization.

Similar to other operations improvement approaches like lean, six sigma or total quality management training and education are key factors of an agile operations transformation. Literature further points out that the concept of agile operations should be implemented in education. Nevertheless, to the author of this research there is no work known addressing the concept of agile operations in education.

Table 5: Key take-aways and delimitation of 'agile operations' concerning this research

Key take-aways	Delimitation
- Agility requires a system approach - Agility counteracts internal and external changes - To adapt quickly on change requires actions on the shopfloor level up to the corporate strategy level as well as adaptions and cooperation across the value network - Implementation of agility is complex and requires know-how and the understanding of external and internal relations - Agility depends on the organization's context and therefore a holistic view is needed - Understanding the business environment and the potential impact of uncertainties on operations is key to the pro-active approach of agility - Monitoring generates the necessary signals to quickly react on change - Aligned with the strategy, pre-defined agility levers are central to quickly respond to external developments - An integrated governance structure to coordinate agility activities is necessary - Management knowledge and competences are crucial for achieving agility	INCLUDES: - The 'corporate agility system' proposed by *Luczak 2017* - Competences related to agility in operations - Methods and tools of the core elements of the corporate agility system: 'agility drivers', 'monitoring', 'strategic alignment', 'agile operations levers', 'governance' EXCLUDES: - Development of 'agile organization' - Corporate culture and behavior - Corporate strategic work - Corporate finance - Marketing

2.3 Basics of competence development

Hoffmann 1999 state that competences are applied to further develop human performance through trainings and education (Hoffmann 1999, p. 281). Further, competence-based learning is promoted in literature and by politics (Aspin and Chapman 2013; Zlatkin-Troitschanskaia et al. 2015; European Commission et al. 2011).

This subchapter describes first the basic definitions of the concept of 'competence' with respect to the focus of this research. Second, it outlines theory, processes and methods of 'learning'. Third, it outlines 'experiential learning' as promising basis for developing operations management related competences in more detail. Finally, this subchapter concludes with a brief summary and the relevant aspects of basic literature and its implications for this research.

2.3.1 Concept of competence

The objective of this section is to create a common understanding for the term 'competence' used throughout this thesis. Therefore, this section defines the basic terms 'knowledge' and 'competence' with its related terms 'skill' and 'learning outcome'. Further, this subchapter introduces evaluation approaches concerning competences and its consisting elements.

Definitions and related aspects

The central term 'knowledge' is in respect to this research referred to as "*[…] the body of facts, principles, theories and practices that is related to a field of work or study.*" (EMPL 2018b) Further, the European Commission states that knowledge results from the assimilation of information through learning (for more details about 'learning' see section 2.3.2 and 2.3.3) (EMPL 2018b). The value of knowledge only becomes visible when this knowledge is converted into a competence to enable corresponding actions (North 2011, p. 38). This is particularly relevant for the conception of training and further education measures (North 2011, p. 38).

In literature, numerous definitions of the concept of competence exist (e.g. Roegiers 2007, p. 156; Sadler 2013, p. 13; Shavelson 2010, p. 44). However, literature also states that the usage of the term 'competence' is very diverse (Eraut 2009, p. 127). Importantly *Blömeke et al. 2013* mention that there is a difference between the terms 'competence' and 'competency'. The latter one is a contributing element to an overall 'competence' and is used more or less synonymously with the term 'skill'. However, a 'large enough' skill might also be referred to as competence in a specific field of action (Blömeke et al. 2013, p. 1). Not only due to this circumstance *Hoffmann 1999* argued that the usefulness of the term itself may be discussed. However, he pointed out that it is important to define the term related to the intended use rather than to "*[…] fight out the 'true' meaning of the term.*" (Hoffmann 1999, p. 281).

Figure 16 illustrates the main elements of the concept of competence concerning this research.

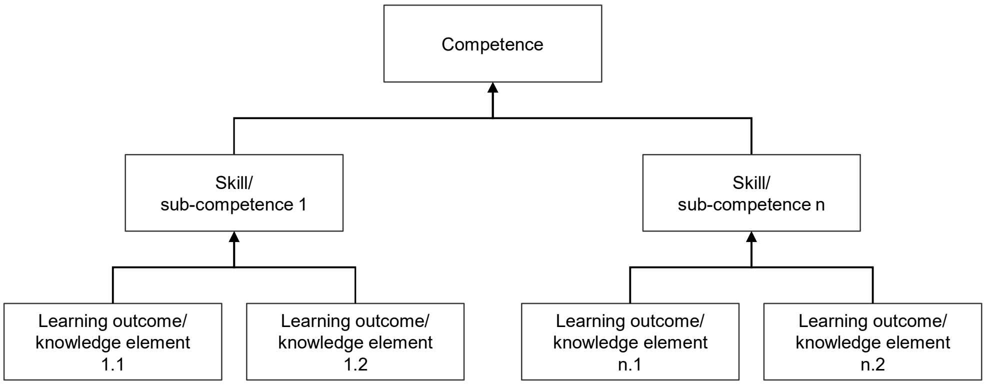

Figure 16: Competence, skill (sub-competence) and learning outcome
(Schaffernicht and Groesser 2016, p. 56)

Competence:
The definition used throughout this research is provided by the European Commission and reads as follows: "*Competence means the proven ability to use knowledge, skills and personal, social and/or methodological abilities, in work or study situations and in professional and personal development.*" (EMPL 2018c) Further it is stated that the term 'competence' describes the ability of individuals to respond to new situations using and applying *"[...] knowledge and skills in an independent and self-directed way."* (EMPL 2018c).

Skill (or sub-competence):
Similar to the term 'competence' also the meaning of the term 'skill' is broad and its use is diverse (Payne 2000, p. 366). This research takes into account as well the definition by the European Commission: "*Skill means the ability to apply knowledge and use know-how to complete tasks and solve problems."* (EMPL 2018d)

As mentioned above, the term skill is used also frequently interchangeably with the term 'competency' (Blömeke et al. 2013, p. 1). For the sake of clarity, the term 'sub-competence' is used solely throughout this thesis in order to avoid miss understanding between the terms 'skill' and 'competency'.

Learning outcome:
The basic element of the concept of competence indicates *what* participants of educational programs should learn (Bloom et al. 1984). Following formal definition of 'learning outcome' recommended by the European Commission is considered: *"learning outcomes are statements of what a learner knows, understands and is able to do on completion of a learning process."* (EMPL 2018a)

Literature highlights the positive impact of using learning outcomes to increase training transfer success (e.g. *Bandura 1977; Locke et al. 1981; Richman-Hirsch 2001; Burke and Hutchins 2016*). Further, *Bloom et al. 1984* argue that specifying learning outcomes is the basis for the design of the learning experience and provides the basis for evaluation techniques. The authors state that the formulation of learning outcomes should be based on conscious choices considering existing data

about the learners and the subject matter itself. (Bloom et al. 1984, p. 4)
Throughout this research, the term ‘learning outcome’ is also referred to as ‘knowledge element’.

Competence development stages:
Competence builds up on knowledge, the ability and motivation to act in the right way (North 2011, p. 38). According to several authors competence development takes place in a cumulative way (e.g. Sternberg 2005, p. 15; Wilhelm and Schroeders 2019, p. 260). One of the most acknowledged models of stepwise competence development is the model by Hubert and Stuart Dreyfus first published in 1980 (Dreyfus 2016, p. 181) and has been used e.g. in nursing, management and computer programming education (Dall’Alba and Sandberg 2016, p. 389). This so-called Dreyfuss-Dreyfuss model consists of five skill stages: (1) beginner; (2) advanced beginner; (3) competent; (4) proficient; and (5) expert (Dreyfus 2016, p. 181). However, not all of these competence-levels are ‘reachable’ within learning programs due to the importance of personal experiences in practice (Schaffernicht and Groesser 2016, pp. 55–56). This stage-based progression of skill or competence development is questioned in an discussion among various scholars summarized by e.g. *Dall’Alba and Sandberg 2016* the authors criticize that “*[…] the focus on stages veils or conceals more fundamental aspects of professional skill development.*” (Dall’Alba and Sandberg 2016, p. 383)

Assessment of competences

Cachay et al. 2012 state that the assessment of intended outcomes is central when participant’s competence development is in the focus. Further, it is also important as source for feedback concerning the improvement of the educational measures and experience from a teaching perspective (Cachay et al. 2012, p. 1147; Glass and Metternich 2020, p. 38).

However, *Glass and Metternich 2020* point out that the basis to enable such a measurement is the definition of a competence itself. Further, the authors propose a competency matrix to breakdown a main competence into its elements (skills and learning outcomes/knowledge elements) as well as observable actions of each competence element. Based on this breakdown the resulting components of a competence can be evaluated (Glass and Metternich 2020, p. 39). Figure 17 shows exemplary such a competence matrix of the main competence ‘conducting the value stream mapping’ (as presented by *Glass and Metternich 2020*).

Main competence	**Sub-competence**	**Observable action**	**Required knowledge**
Conduction the value stream mapping (VSM)	Utilizing the right VSM symbols	Integrating customer, supplier and production planning into the VSM	Knowledge of all the available symbols and the overall process
		Drawing the different process steps	
		Drawing the connecting symbols	Knowledge of the connecting symbols
	…	…	…

Figure 17: Competence matrix (exemplary) (based on Glass and Metternich 2020, p. 39)

Braun and Mishra 2016 comprehensively summarized established approaches of competence evaluations (see Table 6).

Table 6: Comparison of established approaches for competence assessment (based on Braun and Mishra 2016, pp. 51–59)

Approach	**Description**	**Challenges**
Self report	Competences are measured through methods based on the self-perception of students. (Braun and Mishra 2016, p. 51)	- Not free of biases - Does not prove the performance in new and challenging situations
Job requirements	Aims to measure individuals competences directly during performing at the work place (Felstead 2007, p. 62)	- Builds on self-description, not free of biases
Student engagement	Indirect measurement of learning outcomes through focus on students' performance in education activities (Braun and Mishra 2016, p. 51)	- Necessity of an unidirectional relation of activity and learning outcome
Achievement tests	Direct measurement through tasks to solve by evaluating the errors and correct answers (Braun and Mishra 2016, p. 51)	- Mainly knowledge related - Lack of student's motivation
Role-plays	To measure competences students are observed when assigned with different roles and responsibilities to solve complex problem situations (Beard et al. 1995, p. 133)	- Higher effort of applying - Good for assessing complex situations

The competence matrix (Figure 17) and the introduced approaches for competence assessment (Table 6) show that a separation of competence, knowledge/learning outcome and observable action is needed for a more accurate competence assessment. Chapter 4 introduces in more detail the considerations concerning an assessment approach for the empirical part of this thesis.

Competence classes

Due to the complexity of human action and the associated multi-layered nature of dispositions that enable us to do so, in a simplified manner the following four competence classes can be distinguished (Abele et al. 2010a, p. 911): (Erpenbeck and Rosenstiel 2003, XIV)

- *Personal competences*: Basis for other competence classes. Examples are motivation or learning ability
- *Socio-communicative competences*: Define the behavior of individuals in specific situations
- *Professional and methodological competences*: Describe the ability of self-organized problem solving with present knowledge
- *Activity- and implementation-oriented competences*: Overall ability of a person to act actively and holistically self-organized and to direct this action towards the implementation of intentions and plans, either alone or in a team

These competence classes are interrelated e.g. personal competences such as 'motivation' or 'learning ability' are the basis for the development of socio-communicative- and technical and methodological competences as well as for the instant application of activity- and implementation-oriented competences (Tenberg 2011, pp. 93–94).

Further, *Tenberg 2011* describes two types of knowledge: (1) ‘professional knowledge’ and (2) ‘conceptual knowledge’. Professional knowledge refers to knowledge needed on an operational level to perform concrete work steps. Conceptual knowledge refers to a reflection level of specific professional knowledge and determines the capability of undertaking logical problem solving, integrating new information into existing expertise and finding original solutions under non-standard circumstances. (Tenberg 2011, pp. 84–85)

As previously mentioned, knowledge results from the assimilation of information through learning (EMPL 2018b) and subsequently this applies to competence development (North 2011, p. 38). Therefore, the following section reviews literature concerning ‘learning’.

2.3.2 Learning

Based on the gained understanding of competences, the process of learning is in the focus of this subchapter. Related topics of ‘learning theory’, ‘types of learners’, ‘didactic’, ‘instructional design’ and ‘learning (or teaching) methods’ are introduced to create a solid basis for the empirical part of this thesis.

A basic definition of ‘learning’ states that “*[…] learning is the process whereby knowledge is created.*” (Kolb 2015, p. 49) Learning incorporates three criteria: (1) learning contains change; (2) learning is sustainable over time; and (3) learning happens through experience (Schunk 2012, p. 4). *Arrow 1962* stated that learning takes place through problem solving and therefore throughout an activity. He concludes that “*[…] learning is the product of experience.*” (Arrow 1962, p. 155) The importance of experience for the process of learning is also emphasized by *Kolb 1984* where the author points out that to gain knowledge a combination of understanding and transforming experience is necessary or as Revans 1998 puts it: “*[…] there can be no learning without action, and no action without learning.”* (Revans 1998, p. 83)

Learning theories

There is a distinction between individual learning theories with a focus on the individual itself and organizational learning theories where individuals are seen in the context of a social system (Hilgard and Bower 1970, pp. 17–18). Since this research focus on time-limited and undetermined composition of small learning groups organizational learning theories do not take effect. Therefore, the present work considers individual learning theories.

To achieve learning - a transforming process - and to develop competences individuals have to build mental models to generate relations between different tasks (Baartman and Bruijn 2011, p. 128). To describe or predict under which conditions learning is successful different learning theories and principles were developed throughout the past (Ormrod 2014, p. 11). *Ormrod 2014* differs in between ‘learning principles’ (WHAT is important for learning) and ‘learning theories’ (WHY is it important for learning). Further, the author states that the three main views on learning (or ‘learning theories’) are: (1) behaviorism (e.g. Skinner 1976); (2) social learning theory (e.g. Bandura 1977); and (3) cognitivism (e.g. Neisser 2014). Behaviorism understands learning through the relationship of stimuli and responses. The social learning theory puts observation of others in the

center of the learning processes. Besides individual behavior, the thought process or cognition completes the picture of learning from a cognitivism point of view. However, no single theory of these three explains all aspects of the learning process. (Ormrod 2014, pp. 6–8)
Still, learning theories are valuable sources concerning strategy, tactics and techniques of learning processes (Ertmer and Newby 1993, p. 51). The question of HOW an effective learning transfer can be designed is addressed in the further course of this subsection ('Didactic and instructional design').

Table 7 describes the basic underlying assumptions of the three main views on learning and related principles.

Table 7: Learning theories, basic assumptions and related exponents (based on Ormrod 2014, pp. 35-161; Beard and Wilson 2013, p. 261)

Views on learning	**Main underlying assumptions**	**Theories and principles**	**Exponents**
Behaviorism	- Focus of learning is on stimuli and subsequent responses - Internal processes (thoughts, motives) are excluded in investigations - Learning involves change of behavior - Learning results mainly due to external events	- Classical conditioning - Operant conditioning - Punishment	Pavlov, I. Watson, J.B. Skinner, B.F. Thorndike, E.
Social cognitive theory	- Individuals learn by observing others - Learning can occur without change of behavior - Cognition is one important element of learning - Individuals can actively shape their environment	- Modeling - Self-efficacy - Self-regulation	Bandura, A. Rosenthal, T.L. Pajares, F. Zimmerman, B.J.

Cognitivism	- Learning processes may be individual for learners
	- Learning involves internal (mental) change and not specifically an external behavior change
	- Individuals are active part of own learning and not passive parts of environmental events
	- Individuals knowledge, attitudes, beliefs, etc. are interconnected
		- Gestalt psychology
		- Verbal learning research
		- Contemporary cognitive perspectives:
		  - Information processing theory
		  - Constructivism
		  - Contextual theories
			Köhler, W.
			Wertheimer, M.
			Neisser, U.
			Hall, J.F.
			Mayer, R.E.

It is not within the scope of this research to go into further details concerning all the different learning theories. Table 7 refers to scholars of theories and principles in literature for further information.

However, the approach of 'constructivism' with its focus on concrete action is worth introducing due to its continuing actuality (Ertmer and Newby 1993, p. 62; Colburn 2015Colburn 2015, p. 9) and because of its relevance to this work.

Constructivism:
The main principles of constructivism are that learners base sense making of novel situations on their existing understanding and that individuals learning involves an "*[...] active process in which learners construct meaning by linking new ideas with their existing knowledge.*" (Naylor and Keogh 1999, p. 93) Transfer of knowledge occurs by concrete action in authentic tasks situated in meaningful environments (Ertmer and Newby 1993, p. 64). Further, *Bednar et al. 1991* re-inforce this argument and state that rich context is the basis for learning and this context should be a

reflection of real world problems in order to enable the transfer from training environment to reality (Bednar et al. 1991, p. 92). Hence, as *Jonassen 1991* puts it: constructivism encourages to "*[...] create real-world environments that employ the context in which the learning is relevant.*" (Jonassen 1991, p. 11) Learning environment and related aspects are addressed in more detail within section 2.3.3.

Learning styles

A learning style is individual to each person and describes the individual process from starting to concentrate to develop and recall novel information (Dunn 1990, p. 224).
Cassidy 2004 provides an extensive overview of theories concerning learning styles. To provide insights of the composition of such models selected learning styles models are described in the following:

- 'Kolb's Learning Style Inventory' identifies four different types of learners: (1) Accommodator (hands-on experience); (2) Converger (application of theory in practice); (3) Diverger (creative problem solution and discussion); and (4) Assimilator (conceptualization and reflective observation). Further, as these learning styles relate to the experiential learning cycle (see section 2.3.3), Kolb states that learners will cope with some stages better and that learning is still an interactive and continuous process. (Cassidy 2004, p. 430)
- The Model of Honey and Mumford is based as well on Kolb's 'Experiential Learning Model' and was developed specifically for management trainees. The model identifies four learning styles related to Kolb's 'Learning Style Inventory': (1) Activist (active experimentation); (2) Reflector (reflective observation); (3) Theorist (Abstract conceptualization); and (4) Pragmatist (concrete experience). (Cassidy 2004, p. 432)
- According to the 'Dunn and Dunn Model' individuals learning is influenced by the four factors (1) environment (e.g. design, sound); (2) emotional (e.g. motivation, responsibility); (3) sociological (e.g. peers, group); and (4) psychological (e.g. time of day). (Cassidy 2004, p. 435).

Research results show that individuals tend to learn better with their personal learning style however it can be stated that "*[...] no learning style is better or worse than another.*" (Dunn 1990, p. 239)

Didactics and instructional design

The question 'how' instructors achieve an effective learning transfer considers (1) activities and experiences as well as (2) the learning environment (Anderson 2001, p. 3). Related to learning theories and learning styles are the topics of 'didactic' and 'instructional design'. In the following, both terms are defined briefly.

Didactics

Didactics can be described as the science and practice of teaching and learning and deals with all aspects of decisions, reasons, requirements and processes for teaching (Riedl 2004, p. 8). However, in Germany didactics tradition refers to *"[...] teaching aims, subject matter, methods* and *the organizational frame of teaching and learning."* (Meyer 2016, p. 162) This is confirmed by *Riedl 2004* who points out that didactic in a broader sense contains besides objectives and content as well methods and media for the organization of teaching-learning processes (Riedl 2004, p. 8).

Based on the broader sense of didactic *Heimann et al. 1979* proposed the so-called "Berliner Modell" (see Figure 18) which describes the planning and organization of teaching with the main fields of action intention, content, method and media influencing each other considering as well individual and socio-cultural pre-conditions and consequences (Tisch 2018, p. 247).

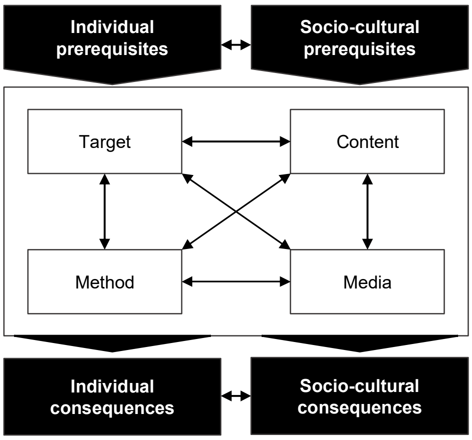

Figure 18: Berliner Modell (based on Heimann et al. 1979, cited by Tisch 2018, p. 247)

Instructional design

Instructional design in contrast has its roots in the United States of America (Zierer and Seel 2012, pp. 1–4). *Gagné 1970* understands the term 'instruction' as the "*...control of the external events in the learning situation.*" (Gagné 1970, pp. 303–304) Further, the author proposes nine events of instruction in order to enable efficient planning (Gagné 1970, p. 345). One of the most influential models of instructional design is the 'Dick and Carey Systems Approach Model for Designing Instruction' (see Figure 19) and was first published in 1996 (Zierer and Seel 2012, pp. 6–7). This model represents a systems approach to instructional design and consists of the following steps: (1) identify instructional goal; (2) conduct instructional analysis; (3) analyze learners and contexts; (4) write performance objectives; (5) develop assessment instruments; (6) develop instructional strategy; (7) develop and select instructional materials; (8) design and conduct formative evaluation of instruction (9) revise instruction; and (10) design and conduct summative evaluation (Dick et al. 2015, pp. 6–8). However, these tasks are part of most instructional design models (Zierer and Seel 2012, pp. 6–7).

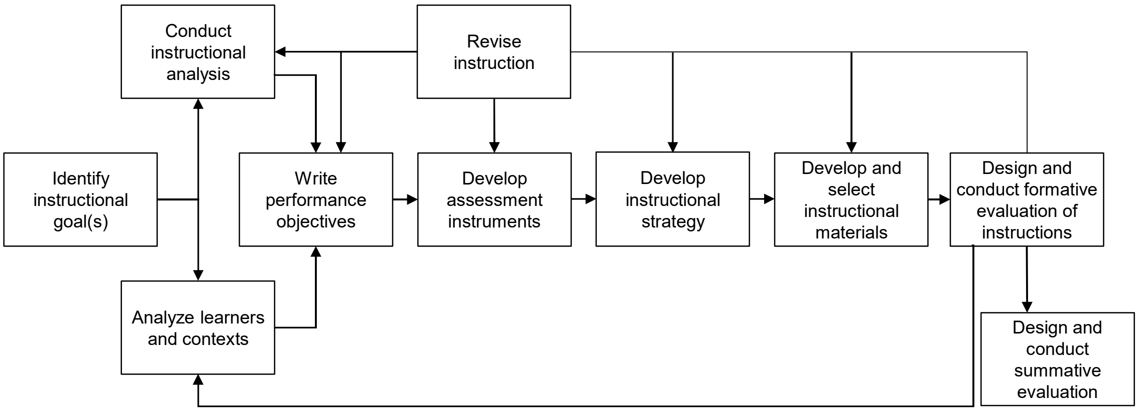

Figure 19: Systems approach model for designing instruction (Dick et al. 2015, pp. 6–8)

The scope of this thesis is not to contribute to either scientific field (didactic or instructional design) but to give at least an overview of the fundamentals of both topics in order to view parts of the further work in context.

Teaching methods

The topics of learning theories, didactics and instructional design as well as learning styles refer at some point to teaching methods and its application in practice as described above.

'Methodology' in this context refers to the science of methods for teaching and instruction including media used to support the learning process (Bonz 2009, p. 3). The appropriate application of theories, methods and environment considering different learning styles improves the overall learning process (Young et al. 2016, p. 131).

In his research about history and status of teaching methods *Henson 1980* lists exemplary types of methods (see Table 8) and states that the term 'teaching method' is used broadly and concepts are numerous and confusing (Henson 1980, p. 3). However, as Table 8 shows, *Henson* distinguishes teaching methods in three subcategories: (1) 'telling'; (2) 'showing'; and (3) 'doing'.

Table 8: Basic types of teaching methods (Henson 1980, p. 3)

Telling	Showing	Doing
- Lecture - Discussion - Panel discussion	- Demonstration - Modeling - Pictures - Written words	- Role-playing - Practice - Exercise - Inquiry based learning - Simulation - Gaming

Throughout the past century there was a strong focus on the teaching methods of 'telling' and especially on large lecture formats in higher education (Sadler 2004, p. 251). These traditional teaching methods still have their advantages and are valuable in many situations (Brandon-Jones et al. 2012, pp. 1474–1475). However, there is a call from educational authorities to introduce active learning (referred to as 'doing' in Table 8) to enhance students involvement in classrooms (Bonwell

1996, p. 31). *Hake 1998* who conducted a study with more than 6.500 participants, states that interactive engagement improves the effectiveness of student learning processes. Further, the author describes methods to increase interactive engagements as *"[…] heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors."* (Hake 1998, p. 65)

These arguments strengthen the importance of concrete experiences for the learning process (Kolb 1984, p. 20). Literature states that 'experiential learning' offers high potential for managerial training due to the possibility to reflect the complexity of practice (Holman 2016, p. 209). This seems especially true in operations management courses due to the required understanding of topics at strategic, tactic and operational levels and the various interrelationships of these levels (Fish 2007, p. 59). Related experiential teaching methods are e.g. simulation games, role-plays or case studies and emphasize the understanding of operations management topics as well as high order skills as e.g. teamwork, presentation or decision-making (Brandon-Jones et al. 2012, p. 1474).

In the further course, this thesis is going to focus upon experiential learning. Related experiential teaching methods as well as the topic of learning environments are introduced in detail in the following subchapter.

2.3.3 Experiential learning

A synthesized statement strengthening the importance of experience in learning is: "A*n ounce of experience is better than a ton of theory*." (Dewey 2004, pp. 157–158).. Experiential learning might tackle critics like 'theoretical', 'passive' or 'not preparing participants for complexity and real world' of business and managerial education (Taras et al. 2013, p. 417). However, several studies show that participants prefer experiential methods and that these methods are vital due to their positive impact on participants learning (Bonwell and Eison 1991, p. 5).

In literature, various definitions of experiential learning exist but due to different interpretations of theorists and practitioners, a single clear definition lacks (Beard and Wilson 2013, p. 24). Gentry 1990 describes the early beginnings and related terms of experiential learning and related fields in research. *Dewey and Dewey 2008* (first published in 1915) discuss 'learning by doing' whereas *Wolfe and Byrne 1975* describe the term 'experienced-based learning' (Gentry 1990, p. 10). Further, the term of 'action learning' is often used synonymously with 'experiential learning' due to the fact that both share theoretical assumptions and similar implications (Zuber-Skerritt 2002).

Table 9 lists notable representatives and their definitions of ‘experiential learning’.

Table 9: Definitions of experiential learning (extended from Beard and Wilson 2013, pp. 24–26)

Source	**Definition**
Boydell 1976, pp. 19–20	“(Experiential learning) is synonymous with ‘meaningful-discovery’ learning… which involves the learner in sorting things out for himself by restructuring his perceptions of what is happening.”
Tumin 1977, p. 41	“The contrast between non-experiential and experiential learning is one between more and less abstract and more and less linguistic sets of symbols that are employed in the transactions in which learning takes place.”
Chickering 1977, p. 613	“Experiential learning means that learning that occurs when changes in judgement, feelings or skills result for a particular person from living through an event or events.”
Kolb 1984, p. 41	“(Experiential learning is) the process whereby knowledge is created through the transformation of experience. Knowledge results from the combination of grasping and transforming experience.”
Hutton 1989, p. 51	“Experiential learning is learning that is rooted in our doing and our experience. It is learning which illuminates that experience and provides direction for the making of judgements as a guide to choice and action”
Saddington 1992, p. 44	“Experiential learning is a process in which an experience is reflected upon and then translated into concepts which in turn become guidelines for new experiences.”
Cantor 1997, p. 1	“Experiential education refers to learning activities that engage the learner directly in the phenomena being studied.”
Jarvis 1999, p. 65	“(Experiential learning is) learning that begins with experience and transforms it into knowledge, skill, attitude, emotions, values, beliefs, senses”
Hale Feinstein et al. 2002, p. 733	“Experiential learning is a participatory method of learning that involves a variety of a person’s mental capabilities. It exists when a learner processes information in an active and immersive learning environment.”
Beard and Wilson 2013, p.26	“Experiential learning is the sense-making process of active engagement between the inner world of the person and the outer world of the environment.”

From the point of view of the author of the present research at hand, these definitions highlight following characteristics of experiential learning: (1) the involvement of participants; (2) the performance of concrete actions; (3) sense-making and reflection of actions; (4) addressing emotions, beliefs, values etc.; and (5) the presence of a suitable learning environment.

Kolb 1984 explains that participants in experiential learning activities must be fully involved without preconceptions, observe and reflect lived experiences, create concepts based on observations and reflections to form logic theories used to solve problems (Kolb 1984, p. 236). In his experiential learning cycle the author formulates that experience can be captured through: (1) concrete experience and (2) abstract conceptualization; whereas the transforming of experience happens in the phases of: (1) reflective observation and (2) active experimentation (Kolb 2015, p. 51). Further, the author states that the learner should “*[...] touch all the bases.*” (Kolb 2015, p. 51)

Figure 20 depicts the experiential learning cycle.

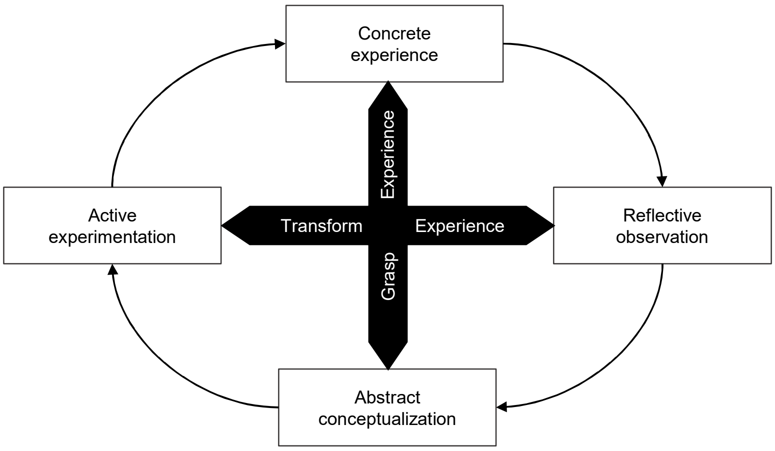

Figure 20: Experiential learning cycle (Kolb 2015, p. 51)

However, in literature different frameworks of experiential learning exist (Zan et al. 2015, p. 344). *Zan et al. 2015* identified existing frameworks and synthesized four common macro phases referring to the experiential learning cycle (Zan et al. 2015, p. 345). Whereas the early models and Kolb's experiential learning cycle relate 'experiences' to 'real-world experiences' the framework proposed by *Freitas and Neumann 2009* focus especially on the use of virtual environments applying 3D and immersive modelling tools (Freitas and Neumann 2009, p. 346). *Tenberg 2011* describes that learning happens especially through combination of (1) explorative or experimentation activities and (2) systematization activities. Systematization activities relate to technical or scientific systematics including e.g. the capturing, comparing or abstracting. Explorative and experimentation activities relate to professional task and the ability to act taking into account the demand for contextualization (Tenberg 2011, pp. 264–266). 'Exploration' in this context describes activities where something new is to identify and 'experimentation' means applying, implementing or realizing (Abele et al. 2015a, p. 94).

Extended from *Zan et al. 2015*, Table 10 shows selected existing frameworks and their phases of experiential learning.

Table 10: Phases of selected experiential learning frameworks (extended from Zan et al. 2015, p. 345)

Phase	***Dewey 1938***	***Lewin 1946***	***Kolb 1984***	***Pfeiffer and Jones 1983***	***Freitas and Neumann 2009***	***Tenberg 2011***	***Zan et al. 2015***
I	Impulse, problem setting	Planning	Concrete experience	Experiencing	Experience (abstract, lived, virtual)	Systematization	Concrete experience - briefing - as-is exploration
II	Observation and problem determination; solution proposal	Execution	Reflective observation	Sharing	Exploration (observation, activity, interaction)	Exploitation / experimentation	Reflective observation - sharing - re-elaboration
III	Reasoning; Experimentation	Investigation	Abstract conceptua-lization	Processing	Reflection (meta-reflection)	Reflection	Abstract conceptualization - concept transfer - to-be planning
IV	Judgement		Active experiment-ation	Generalizing	Forming abstract concepts	Evaluation	Experimentation - application - consolidation
V				Applying	Testing in different situations (abstract, lived, virtual)		

In addition to the experiential learning cycle (where 'application' is the basis for understanding) a second approach to learning processes is 'information assimilation' where the theoretic content is introduced first and experimentation/application follows in a second step (Abele et al. 2017, p. 819). Exemplary the phases of the framework proposed by *Tenberg 2011* might be structured according to the experiential learning cycle: 'exploration/experimentation' followed by 'systematization'; or as 'information assimilation' approach: 'systematization' before 'exploration/experimentation'.

There is a need to understand the significance of the learning content and this involves to sense the consequences of resulting actions (Dewey 1997, pp. 68–69). Related to such a reflective practice is the topic of 'single loop' and 'double loop' learning proposed by *Argyris and Schön 1978* (see Figure 21). Single- and double loop learning is discussed especially in the context of organizational learning but can be applied as well on individuals (Argyris and Schön 1978, pp. 3–4). The single loop learning is not essentially different from Kolb's learning cycle where the learner asks himself: "A*m I doing the thing right?*" (Beard and Wilson 2013, p. 260). Whereas double loop learning happens when an error occurs and is corrected involving the adaptations of basic assumptions (Argyris and Schön 1978, pp. 3–4). Hence, in the double loop learning cycle the learner asks himself: "*Am I doing the right things*?" (Beard and Wilson 2013, p. 260).

Figure 21 shows single loop and double loop learning based on *Argyris and Schön 1978.*

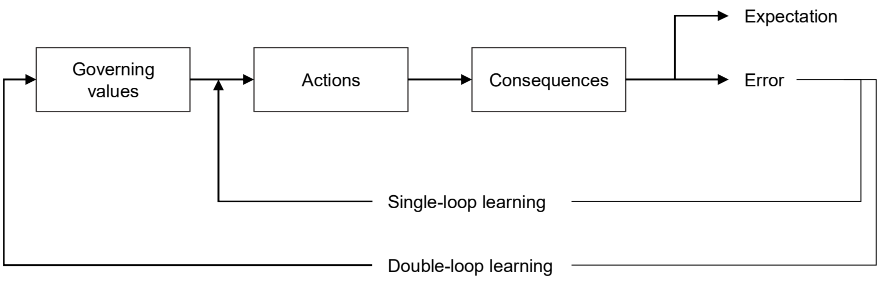

Figure 21: Single-loop learning and double-loop learning (based on Argyris and Schön 1978, pp. 142–143)

Cannon et al. 2014 state that the theory of single-loop and double-loop learning deals with the struggle of learners to change their basic assumptions and subsequently their behavior. Further, the authors point out that such change involves the questioning of values as well as emotional engagement (Cannon et al. 2014, p. 386). To address the internal (emotions, reasoning and change) and external (environment, activities) factors *Beard and Wilson 2013* propose practical considerations in order to enhance the learning process of individuals (see Table 11) (Beard and Wilson 2013, p. 7).

Table 11: Practical considerations for learning (based on Beard and Wilson 2013, p. 7)

Where?	**What?**	**How?**	**Hearts?**	**Minds?**	**Change?**
Where does learning take place?	What will the learners actually do?	How will the learners receive the experience?	Is emotional engagement considered?	What do learners need to know?	How can learners be encouraged to change?

In order to be able to answer these questions the following subchapters addresses in detail characteristics of learning environments and experiential learning methods.

Experiential learning environments

Constructivist learning environments enhance learning and meet the demands of the world of work, especially through their possibilities for self-directed, problem-oriented and case-based learning (Gerstenmaier and Mandl 2011, p. 173). Throughout this research the term 'learning environment' is based on constructivism theory and its underlying understanding of learning as active and continuous process emphasizing 'understanding' (Tynjälä 1999, pp. 364–366). A learning environment can be defined as "*[…] particular place where individuals can learn by using a variety of information resources and tools that are designed and allocated in the pursuit of learning objectives.*" (SpringerLink 2020) The learning environment is not just considered as the 'physical' place but further includes e.g. constructive feedback, clear learning objectives, transporting the relevance of the topics, motivational elements or opportunities for reflection and discussion (Struyven et al. 2006, pp. 280–281). Furthermore, besides the physical environment and the instructional design of the content especially participant's perception of all these measures influences the learning process (Entwistle 1991, p. 202). *Tynjälä 1999* concludes that learning environments based on constructivism especially enable learning results needed in professional life (Tynjälä 1999, p. 424).

Honebein et al. 1993 also building on constructivism theory, explains that 'experience' is connected to the physical environment as well as cognitive and physical tasks performed in this physical environment. The author further emphasizes the importance of the larger context in which learning occurs using the example of 'learning about photosynthesis'. Whereas 'growing one's own tomato plant' contributes to the learning about photosynthesis a larger purpose like 'participating in a contest to grow the largest tomato plant' further enhances the learning process as a clear objective is given (Honebein et al. 1993, pp. 87–88). Strengthening the argument of 'context', *Bednar et al. 1991* call for "real worldness" to create an authentic learning experience due to the constructivist view that pure information without context cannot be remembered. The learning environment is responsible to link pure information with context and embedded knowledge *(Bednar et al. 1991, p. 95)*.

Learning environments therefore are able to enhance or hinder the process of learning (Borko and Putman 2009, p. 675). In this context, *Caine and Caine 1990* introduced principles of how context and environments contribute to enhance learning of participants (see Table 12).

Table 12: Principles of learning environments influencing the process of learning (based on Caine and Caine 1990, 66–69)

1. *All learning engages the physiology*
   Involvement of different senses enhances learning.
2. *The brain/mind is social*
   Social activities increase learning
3. *The search for meaning is innate*
   Working on one's own ideas and projects increases learning
4. *The search for meaning occurs through patterning*
   A bigger contextual picture foster understanding
5. *Emotions are critical to patterning*
   Motivation is an important factor for learning outcomes
6. *The brain/mind processes parts and wholes simultaneously*
   Learning activities embedded in real-life projects increase understanding
7. *Learning involves both focused attention and peripheral perception*
   Focus on the content as well as on the physical environment matters to learning
8. *Learning is both conscious and unconscious*
   Reflections of performed experiences is important to the process of learning
9. *There are least two approaches to memory*
   Stimulation of theoretical and experiential knowledge in appropriate combination is important
10. *Complex learning is enhanced by challenge*
    Challenging and empowering learning environments foster understanding.

As pointed out by *Caine and Caine 1990,* the literature emphasizes that motivation is one of the most powerful psychological concepts in education (Vallerand et al. 2016, p. 1004). Strengthening this argument, *Pirker 2017* proposes guidelines to create motivational learning environments emphasizing on engagement elements and 'immersion' (Pirker 2017, pp. 193–195). 'Immersion' can be defined as "*[...] subjective impression that one is participating in a comprehensive, realistic experience.*" (Dede 2009, p. 66) *Pirker 2017* argues that four different forms of immersion exist and that the use of different teaching methods and technological aids enables the creation of immersive experiences: (1) 'spatial immersion' – natural environment design; (2) 'tactical immersion' – enable participants to react quickly and automatically in learning situations; (3) 'strategic immersion' – activities to challenge participants to observe and calculate; and (4) 'narrative immersion' – put activities in a larger context including interesting story elements and environment (Pirker 2017, pp. 193–195).

The following section describes selected experiential teaching methods in order to design a supporting learning environment.

Experiential teaching methods

In the previous section 'Teaching methods' general methods are listed and arguments for experiential methods especially in the field of operations management were provided. To develop experiential learning activities for operations management topics instructors have to create experiences integrating connections amid strategic, tactical and operational decisions (Fish 2007, p. 59). To actively involve participants of operations management courses various methods, including case studies, scenario learning, business games or role-plays exist (Hale Feinstein et al. 2002, pp. 733–734; Riis et al. 2000). Table 13 lists general strength and limitations of experiential learning methods based on a literature survey performed by *Brandon-Jones et al. 2012*.

Table 13: Strength and limitations of experiential methods (based on Brandon-Jones et al. 2012, p. 1486)

Strength of experiential methods	Limitations of experiential methods
- Learning by doing. Participants are actively involved in their learning process, aiding to gain knowledge - Stimulates curiosity of the subject - Group work often required - Acquisition of higher order skills – interaction, communication, information gathering, conflict resolution, presentation, and decision-making - Transfer of theory to practice - Chance to try out ideas in a not-real environment - Good for highly interconnected subjects such as operations management	- Inefficient in delivering large amounts of information - Less useful for acoustic learners - Potential for some participants to dominate the activities - Risk of focusing too much on "winning" rather than learning - May require specific learning environment - Time-consuming for students and faculty - Less control of learning process for the faculty than by traditional teaching methods

The application of combinations of experiential teaching methods enhance the range of meeting different individual learning styles of participants and therefore contributes to an efficient learning process (Bonwell 1996, p. 33). In the following selected experiential teaching methods (case method, scenario method, business game, role-play) relevant to this research work are introduced.

Case method

Case studies can be defined as "*[…] stories with an educational message.*" (Terry 2012, p. 28) A case study describes, emulates or simulates a realistic situation and puts the participant in the center of decision-making (Ellet 2018, p. 12). Case studies have three characteristics: (1) it deals with a substantial business subject; (2) it provides appropriate amount of information as basis for analysis; and (3) it does not provide conclusions (Ellet 2007, p. 13). Participants are entitled on their own knowledge while reading, analyzing, elaborating conclusions and discussing their own opinions with peers based on case information (Ellet 2018, p. 6). Once analyzed the contextual information, participants apply different learning methods including group discussion, problem-based learning, brainstorming or presentations and all combined with instant peer feedback throughout a case study (Bonney 2013, p. 187).

Scenario method

Scenarios are relevant for the treatment of business and economic problems and familiarize participants with a strategic planning method from business practice (Brettschneider 1999, p. 207). The scenario method is characterized by the fact that learners gain relevant system or contextual knowledge and recognize dependencies, effects and interdependencies of factors in a complex system (Bonz 2009, p. 158). Participants develop future scenarios linking quantitative and qualitative data, own assessments and opinions resulting in a detailed description of future situations from a holistic perspective (Albers et al. 1999, p. 12). Central is the aim to promote holistic process thinking (Albers et al. 1999, p. 59). The scenario method aims to integrate (1) taking into account the interdependencies between factors; (2) the application of knowledge and systems thinking; and (3) the impact assessment that determine a system and its future development (Bonz 2009, p. 158).

Business game

A business game involves "*[...] interactions among groups of players (decision makers) placed in a prescribed setting and constrained by a set of rules and procedures.*" (Hsu 1989, p. 409) Business games aim at the simulation of decision processes illustrating real-life situations as the basis for learning processes (Bonz 2009, p. 136). Commonly business games emphasize on a company or a certain organizational area of that company providing e.g. financial, demographic or market related information to take decisions on e.g. production rates, marketing strategies, pricing or resource allocation (Hale Feinstein et al. 2002, p. 736). Business games are typically double-sided: (1) the model that defines the framework and processes the input information; and (2) the actual game as action area for the players (Bonz 2009, p. 139). Further, a business game can be described as 'onput-process-output' model as illustrated in Figure 22 (Lewis and Maylor 2007, p. 138).

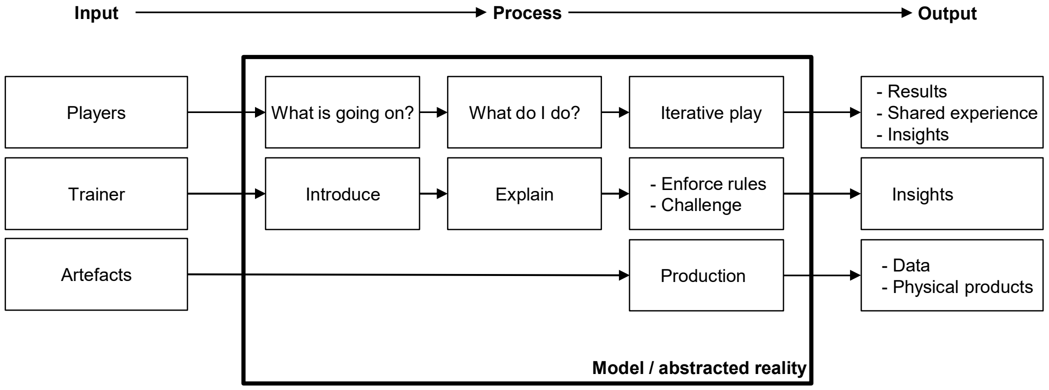

Figure 22: 'Input-process-output' model of business games (Lewis and Maylor 2007, p. 138)

Characteristics of a business game are: (1) acting in complex situations; (2) decision-making considering interdependencies; and (3) forward-looking planning taking into account probable potential reactions (Bonz 2009, p. 139). The general learning process of business games follows in principal three phases: (1) 'experience' – game play, decision input, interaction; (2) 'content' –

dissemination of ideas or concepts regarding theoretical principles; and (3) 'reflection' – feedback in form of game results or administrator feedback (Gentry 1990, pp. 67–68). Advantages of business games are: problem situations might be framed in time; effects on a company due to participants actions can be shown; a large variety of business problems is tangible; and the possibility to obtain a transparent overview of otherwise not easily recognizable side and long-distance effects of decisions (Blötz 2008a, pp. 34–35). Business games are essential tools in management education to develop the ability to act and are used since decades (Gelders and Pintelon 2000, p. 84; Hale Feinstein et al. 2002, p. 736; Bonz 2009, p. 138). For more detailed information see e.g. *Blötz 2008*.

Role-play

A role-play can be described as learning activity where participants immerse themselves in predefined roles to interact in a specific situation with others which enables to "*[...] feel what is at stake.*" (Hsu 1989, p. 409) Through the contextual simulated situation role-plays enables learners to develop a deep understanding of social relationships and an increased awareness of own actions during activities to solve the given problem (Hale Feinstein et al. 2002, p. 735). Role-plays are suitable tools to transfer knowledge and likewise to change behavior (Lira et al. 1975, p. 617). Typically role-plays proceed through the following phases: (1) information; (2) preparation; (3) play experience; (4) discussion; (5) summary of findings; and (6) generalization- and transfer phase (Bonz 2009, p. 141).

Similar to the anatomy of business game approaches, role-plays can be divided into three areas ('role-play environment', 'participants' and 'role-play activities') with sub-items as depicted in Figure 23 (Hsu 1989, p. 422).

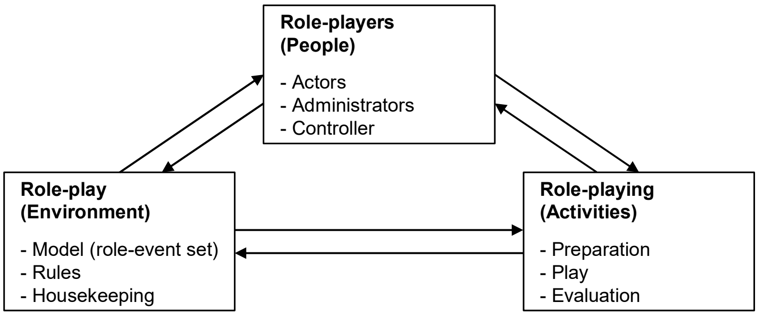

Figure 23: Anatomy of a role-play (Hsu 1989, p. 421)

Hale Feinstein et al. 2002 report that a limitation of role-plays is the fact that participants get instant feedback from peer players that might not be congruent with the actual real-world outcomes in the simulated situation. Therefore, due to the dynamic interaction among participants a clear set of rules and a basic understanding of the situation itself is obligatory (Hale Feinstein et al. 2002, p. 735).

2.3.4 Summary: Competence development and experiential learning

Competences describe the ability of individuals to apply knowledge and skills to respond to new situations. They can be broken down into skills and further into learning outcomes. These learning outcomes describe '*what*' participants of learning programs should learn. Related to the definition of competences and the design of learning programs is the assessment of intended outcomes to (1) guarantee participants' learning and (2) to further develop learning programs. The application of the concept of competence to design trainings and education systems is promoted by politics and in literature.

The term 'learning' describes the process of knowledge creation. Learning is a transforming process and individuals need to build mental models to identify relations between different tasks to gain understanding. In literature, three main theories of learning exist: (1) behaviorism; (2) social learning theory; and (3) cognitivism. However, none of these theories covers all aspects of learning. Nevertheless, these theories are valuable sources concerning strategy, tactics and techniques to enhance participants learning. Especially relevant in this context to this research is 'constructivism', which is based on the theory of 'cognitivism'. Constructivism emphasizes active learning where participants learn by linking new ideas with their existing experiences.

In addition, personal learning styles refer to a person's own preferred way to remember new information and generate knowledge. Individuals tend to learn better with their personal learning style. Didactics and instructional design aim to support training development concerning activities, content, methods and media. The usage of different teaching methods throughout learning programs enhances the overall learning process by meeting different individual learning styles. Especially experiential teaching methods enable the transfer of complex topics such as operations management. Experiential learning definitions highlight (1) the involvement of participants; (2) the performance of concrete actions; (3) sense-making and reflection of actions; (4) addressing emotions, beliefs, values etc.; and (5) the presence of a suitable learning environment. The learning environment is not just considered as the solely physical place where learning happens. It comprises as well e.g. opportunities to reflect, feedback, clear and transparent learning objectives, context, motivational aspects or reasoning. The learning environment as a whole is responsible to link pure information with context and embedded knowledge. Further, consulted literature states that learning environments based on constructivism enable the development of competence needed for professional life.

Table 14: Key take-aways and delimitation of 'basics of competence development' concerning this research

Key take-aways	Delimitation
- The concept of competence enables outcome driven development of learning programs - Competence assessment is necessary to ensure learning and to further develop learning programs - Scientific fields of didactics and instructional design support the design of learning programs - Learning is strongly related to experience - Experiential learning with its strong focus on participants involvement promotes experience and thus the learning process - The learning environment links information with context and enables authentic (learning) experiences - The application of experiential learning methods has the potential to enhance participants motivation, engagement and understanding	INCLUDES: - Concept of competence as basis for training course development - Experiential learning and consideration of its implication on learning environments - Consideration of different experiential learning methods to enhance participants learning process EXCLUDES: - Development or contribution to the research fields of 'learning theory' and 'learning styles'

2.4 Learning factories

Learning factories are installed in academia and industry to address challenges in "*[…] research, innovation transfer, education and training.*" (Tisch and Metternich 2017, p. 89) Throughout the past 20 years research confirmed the success of learning factories for the development of operations management competences (e.g. Abele et al. 2010b, p. 240; Cachay and Abele 2012, p. 639), especially by transporting the principle of experiential learning (Zan et al. 2015, p. 334).

This chapter defines the term 'learning factory' and its origin. Further, it describes in more detail (1) the concept and principles of learning factories; (2) exemplary domains and related competences addressed in existing learning factory courses; and (3) shows strength and limitations of learning factories concerning competence development and as learning environment in general. This chapter concludes with a brief summary of relevant aspects of the presented literature and its implications for this research.

2.4.1 Definition and historic development

The two constituting words of 'learning' and 'factory' describe the purpose of learning factories very well – namely providing a 'learning' process situated in a 'factory' environment (Wagner et al. 2012a, p. 110). Strengthening this argument, *Enke et al. 2016* describe learning factories as models of value chain sections from an operational perspective and as complex learning environments to enable competence development from a teaching perspective (Enke et al. 2016a, p. 2). However, since the implementation of learning factories different definitions are framed (Abele et al. 2017, pp. 808–809). An early definition of the concept of learning factories reads as follows: "*The learning factory recognizes the need for both the intellectual and physical blending of activities as a necessary means of anchoring both the knowledge and the practice.*" (Jorgensen et al. 1997, pp. 103–104)

Abele et al. 2017 provided an extended literature review of learning factories. The authors state that beside various early definitions of single learning factories a scientific discussion started in 2010. Further, the authors analyzed definitions in literature along following dimensions: (1) purpose; (2) process; (3) setting; (4) product; (5) didactic; and (6) operating model of learning factories (Abele et al. 2017, p. 808). Figure 24 depicts the basic content of these dimensions. Based on these dimensions a learning factory morphology to classify learning factory concepts was developed (see Tisch et al. 2015b). This morphology can be seen in Appendix A and is described in detail in *Abele et al. 2019* (see pp. 100-118).

Based on their research *Abele et al. 2017* conclude that the most comprehensive definition of learning factories is the one agreed upon at the corresponding CIRP[6] Collaborative Working Group (CIRP CWG) printed at the CIRP Encyclopedia of Production Engineering:

"*A learning factory in a narrow sense is a learning environment specified by*

- *processes that are authentic, include multiple stations, and comprise technical as well as organizational aspects,*
- *a setting that is changeable and resembles a real value chain,*
- *a physical product being manufactured, and*
- *a didactical concept that comprises formal, informal and nonformal learning, enabled by own actions of the trainees in an onsite learning approach"*
  (Abele 2018).

Learning factories in a broader sense (see Figure 24) modify the narrow definition using e.g. (1) virtual versions of value chains (e.g. *Riffelmacher 2013*); (2) remote learning of trainees (e.g. *Görke et al. 2017*); or (3) services instead of hardware products (e.g. *Sadaj et al. 2020*) (Abele et al. 2015b, p. 3).

Learning factory features

Purpose	Teaching and/or training and/or research
Process	- Authentic - Multi stage - Technical and organizational
Setting	- Changeable - Real or *virtual**
Product	Physical or *service***
Didactics	- Concept based - Formal and informal learning - Own actions of trainees - On site or *remote learning****
Operating model	Sustainable plan allows the ongoing operation (desired)

Learning factory types

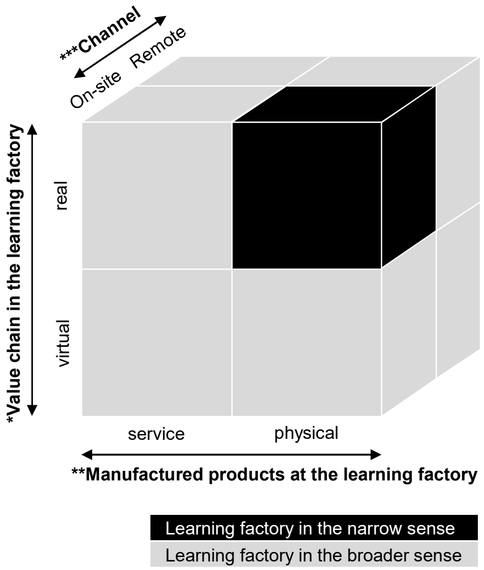

Figure 24: Key features and delimitation of narrow and broad definition of learning factories (Abele et al. 2015b, p. 3)

The definition provided by *Abele 2018* is broadly accepted in literature and used by various authors of different institutions (e.g. *Sudhoff et al. 2020*, *Küsters 2018*, *Tisch 2018*). Likewise, the present research considers this definition of learning factories as basis.

In addition to the term 'learning factory' different notions for partly similar concepts like 'knowledge factory' (e.g. Roth et al. 1994), 'teaching factory' (e.g. Mavrikios et al. 2013), or 'model

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[6] The International Academy for Production Engineering – see www.cirp.net (2020-11-20)

factory' (Zan et al. 2015) are used. However, as these concepts differ in some aspects from the concept of learning factories (Tisch et al. 2016, p. 1357; Abele et al. 2017, p. 804), this research refers solely to the term 'learning factory' and the chosen definition.

In regard to the historical background of learning factory concepts following three phases can be identified: (1) first individual learning factories with a prominent example at Penn State University; (2) implementation of independent learning factories mainly in Europe; and (3) learning factory networks and scientific work on the subject of 'learning factories' (Tisch 2018, pp. 44–46).

Phase I

In 1994 the Penn State University coined the term 'learning factory' due to a received grant for the development of a learning environment to enhance hands-on engineering design education (Jorgensen et al. 1997, p. 106). *Jorgensen et al. 1997* state that this learning factory was developed as the center of a new curriculum to support all courses and activities within an industrial manufacturing environment – from rapid prototyping to finished products including e.g. assembly, test and design studio. Further objectives were to establish a strong collaboration with academia, industry, and government (Jorgensen et al. 1997, p. 106). Earlier in the first phase of learning factory installation was the so-called 'CIM-Lernfabrik' (german term for 'learning factory') at the Fraunhofer Institute for Industrial Engineering (IAO) Stuttgart focusing on aspects of computer integrated manufacturing (Reith 1988, p. 583).

Phase II

Starting around the year 2010 various independent implementations of learning factories occurred across Europe (Wagner et al. 2012a, p. 111). In their research *Wagner et al. 2012a* performed a literature survey and an additional questionnaire study to identify and analyze 25 research and development organizations with learning factories established. The intended objective was to identify learning factories with a focus on changeability. Additional results amongst others are that the terminology is still developing and that there is a need for joining efforts to develop learning factory concepts and related teaching approaches (Wagner et al. 2012a, pp. 112–114). Two years later *Micheu and Kleindienst 2014* identified in their study already 51 learning factories whereas the majority of 32 are situated at academic institutions (Micheu and Kleindienst 2014, p. 403).

Phase III

The academic discussion concerning learning factories gained momentum with the first CIRP sponsored 'Conference on Learning Factories' (CLF) and the foundation of the 'Initiative on European Learning Factories' (IELF) in 2011 (Abele et al. 2019, p. 81). This initiative aims at joint research activities, improvement of the learning factory concept, increase its visibility as well as the organization of the yearly held CLF (Abele et al. 2019, p. 81). As mentioned above, in addition the CIRP CWG on learning factories was initiated and organized global activities such as forming a joint understanding or strengthening the link between industry and academia from 2014 to 2017 (Abele et al. 2017, p. 804). Continuing the global efforts, the IELF decided to expand its activities and is to the present known as 'International Association on Learning Factories' (IALF)[7] (Abele et al. 2019, p. 81). The 10th CLF held in 2020 with 90 published papers and 165 participants from 28

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[7] See: https://ialf-online.net/ (2020-11-02)

different countries (CLF2020 2020) shows the continuing success of these initiatives. Due to the potential of learning factories in dissemination of divers engineering topics, the number of installed learning factories at universities across Europe is growing steadily in the past years (Sudhoff et al. 2020, p. 119).

2.4.2 The learning factory principle

Dehnbostel 2009 describes three basic forms of work-based learning: (1) work-integrated learning; (2) work-connected learning and (3) work-oriented learning. Work-integrated learning describes learning taking place at the origin workplace (e.g. 'on-the-job-learning'). Whereas the place of work and learning is separated by both work-connected and work-oriented learning. Work-connected learning directly links learning processes and the place of work while learning is not intended to occur during day-to-day work tasks (e.g. 'quality circles'). Work-oriented learning separates the workplace and work processes from the learning process and takes place in specific locations. One form of work-oriented learning is learning in simulated work and production processes (e.g. 'learning factories') (Dehnbostel 2009, pp. 2631–2632).

Therefore, learning factories contribute to emphasize production engineering practice (Jorgensen et al. 1997, p. 104). This is especially true for the development of competences in the field of production process optimization (Cachay and Abele 2012, p. 639). Learning factories are complex systems that can be interpreted and designed both as learning environments and as partial models of real factories (Tisch 2018, p. 60). Therefore, learning factories constitute a comprehensive framework as constructivist learning environment (see chapter 2.3.3) for the development of competences (Cachay and Abele 2012, p. 639). The aim of the concept is not to serve as a simple training room for production engineering practice (Abele et al. 2010a, p. 909). Rather, it provides a learning environment that enables a diverse alternation of understanding, cognition, application and reflection processes in a subject-specific context (Abele et al. 2010a, p. 909). Thus, the incorporation of technologies based on real manufacturing systems besides a didactical concept is needed (Tisch et al. 2016, p. 1357). Figure 25 shows challenges to real industry production sites and the principle of the learning factory concept to address such challenges.

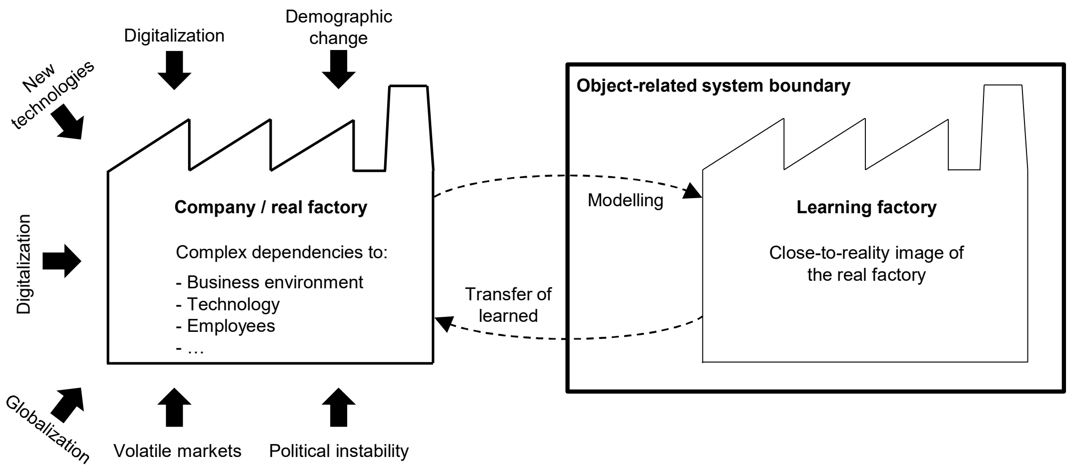


Figure 25: Relation between real factory and modelled learning factory environment (based on Tisch 2018, p. 68)

To address intended competences on more than on one factory level (network > factory > segment > system > cell > work station – Wiendahl et al. 2015, p. 108) system boundaries for each factory level of the learning factory environment need to be defined (Tisch et al. 2016, p. 1362). Figure 27 describes these factory levels in more detail.

The effective competence transfer is then enabled by an active learning approach based on problem solving of authentic production challenges and the alternation of thinking (theoretic input) and doing (practical exploration/experimentation) (Enke et al. 2016a). As described in chapter 2.3.3 there are two approaches to the learning process: (1) the experiential learning cycle; and (2) 'information assimilation' where the cycle starts with theoretical derivation of methods, principles, etc. The learning factory concept fosters both approaches (Abele et al. 2017, p. 819). Figure 26 shows the application of these two approaches of learning process to the learning factory approach.

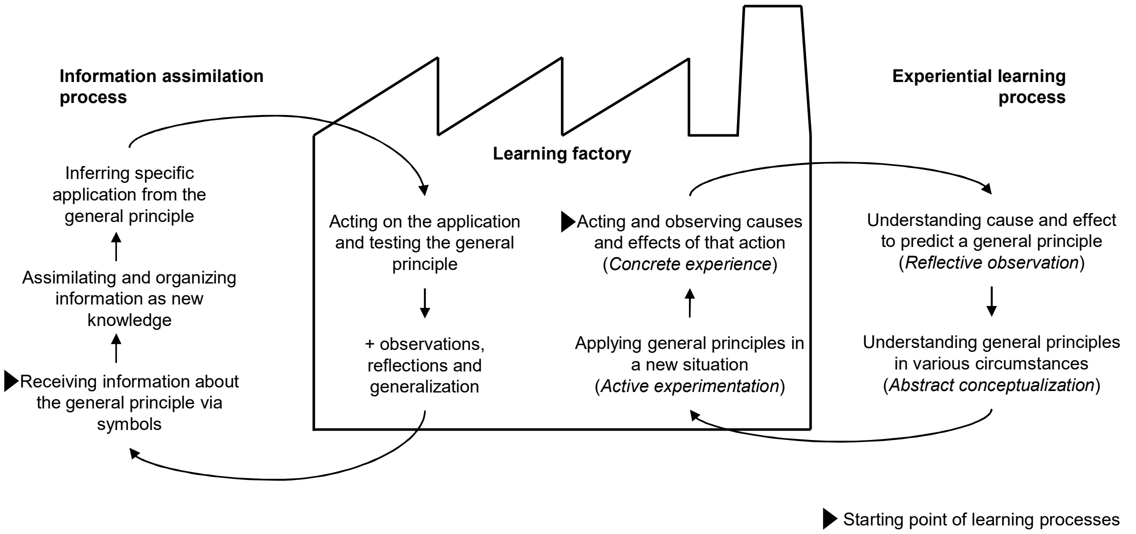
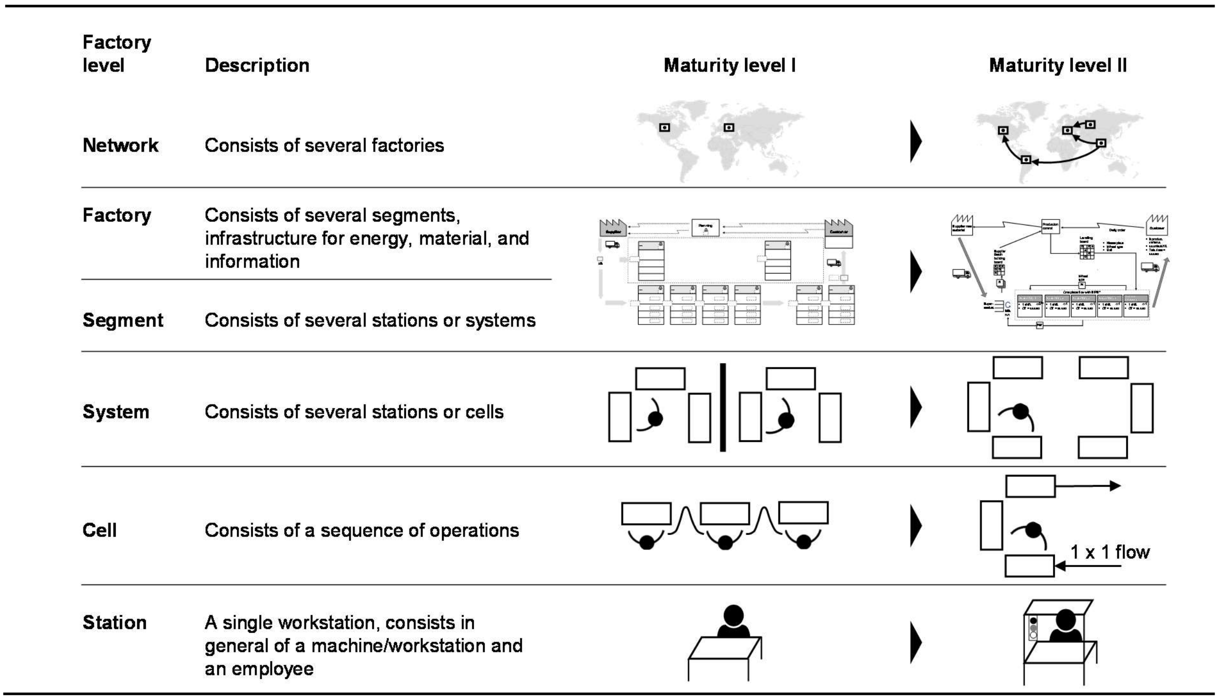


Figure 26: Information assimilation and experiential learning and the learning factory concept (based on Tisch and Metternich 2017, p. 91)

As described in *Tisch and Metternich 2017* and *Tisch et al. 2013,* a teaching module in a learning factory course can start with theory introduction (e.g. methods, principles) of how to address issues and then to apply those information directly at the learning factory. Followed by a reflection and generalization phase. The second approach ('experiential learning process') starts with a concrete experience to see (and identify) first-hand the issues at the learning environment followed by theoretical derivation of e.g. methods, principles, etc. to improve the situation. Next step is then the improvement of the learning factory system in order to apply theoretical derived knowledge and to test, observe and reflect the impact (Tisch et al. 2013, p. 583).

Tisch et al. 2016 describe how to enable both of the mentioned learning approaches at learning factories. As a result, learning factories are built upon at least two different maturity levels. A suboptimal setup to provide participants to experience of open issues to identify; reflect; and address as well as the possibility to improve. In addition, there must be a target state defined that should be achieved by the use of the learning content by the participants. Further, these (at least) two necessary setups must exist for each learning module and topic as well as on the involved learning factory levels where competence development is intended (Tisch et al. 2016, p. 1362).

Figure 27 illustrates these two setups exemplary for each factory level.



Factory level	Description	Maturity level I	Maturity level II
Network	Consists of several factories		
Factory	Consists of several segments, infrastructure for energy, material, and information		
Segment	Consists of several stations or systems		
System	Consists of several stations or cells		
Cell	Consists of a sequence of operations		
Station	A single workstation, consists in general of a machine/workstation and an employee		

Figure 27: Learning factory setups for factory levels (exemplary) (Tisch et al. 2016, p. 1362)

However, as previously mentioned learning factories in a narrow sense process hardware products (Abele et al. 2015b, p. 3). Three basic possibilities for such a product within a learning factory production system exist: (1) market-available products; (2) didactically pre-arranged products (e.g. LEGO blocks); or (3) products developed by participants throughout the learning factory experience (Tisch et al. 2016, pp. 1361–1362). Decision criteria for products are amongst others reusability, the ability to map several stages of the value chain, compliance with constraints such as available workspace, machines, etc., economic criteria and didactic factors such as the ability of participants to learn production steps or the match of the product with the learning content (Küsters 2018, p. 140).

As mentioned before, the single existence of an infrastructure without a didactic concept (e.g. learning center) cannot be defined as learning factory because there needs to be didactical concept in place (Abele et al. 2017, p. 809). Therefore, learning factory concepts need to answer following question: "*Who should learn what, from whom, when, with whom, where, how, with what and for which purpose?*" (Zierer and Seel 2012, p. 2) As stated by *Reiner 2009,* the (didactic) concept of learning factories depends on: (Reiner 2009, p. 85)

- Close to reality production processes and products to increase the ability to demonstrate and reduce the transfer to the company
- Complete value stream, including material and information flow, to illustrate the complexity of reality concerning the interaction and relationship between all elements of the learning factory system
- Versatility and flexibility of the learning factory infrastructure as a basis for the real application (analysis, planning and implementation) of the methods. The training participant must be able to transform the value stream and experience the effects

Especially for students the opportunity to experience real industrial challenges in an authentic production environment is highlighted in literature (Tisch et al. 2016, p. 1358). However, recently the learning factory approach gets attention from companies to qualify specialists on shop floor as well as on top management level (Kreimeier et al. 2014, pp. 184–185). The duration of learning factory based courses can vary from just a few days for industrial employees due to their day-to-day work up to several weeks for student projects (Tisch et al. 2016, p. 1358). Thus, especially the short time frame for industrial employee trainings results in the necessity of rapid knowledge transfer with an strict pre-structured learning process (Tisch et al. 2016, p. 1358).

Therefore, literature emphasizes the need for a structured procedure for the development of the learning factory environment itself, intended teaching topics on a meso level and for each specific learning situation (Tisch et al. 2016, p. 1359). Details concerning the development of learning factories and single learning modules is addressed in more detail throughout chapter 2.5.

2.4.3 Potentials of learning factories

To enhance the transferability from operations improvement process methods to students and industrial employees using a close-to-reality manufacturing environment is the reason for the existence of learning factories (Kreimeier et al. 2014, p. 184). Thus, effective competence development is one of the main targets of learning factory training courses (see e.g. Jorgensen et al. 1997, p. 106; Abele et al. 2010a, p. 912; Cachay et al. 2012, p. 1152; Kreimeier et al. 2014, pp. 184–185; Abele et al. 2015b, p. 1). Further, learning factories can be applied in research (Enke et al. 2016b, p. 224) and innovation transfer (Tisch and Metternich 2017, pp. 90–92). Concerning research two basic application possibilities exist: (1) 'research enabler' – learning factory facilitates the problem identification and solution verification (Abele et al. 2017, p. 817); and (2) 'research object' to research didactic-methodological issues (Kemény et al. 2016, p. 51). Related to 'innovation transfer' learning factories provide the potential for demonstration of up-to-date technologies and necessary know-how (Abele et al. 2017, p. 817).

Cachay et al. 2012 show in their research show that participants of learning factory based courses *"[…] have a greater application-performance and a higher degree of action-substantiating knowledge […]"* compared to traditional learning settings (Cachay et al. 2012, p. 1152). Further, the positive effect on participants learning processes of learning factories is confirmed by e.g. *Abele et al. 2010a* and *Cachay et al. 2012*. However, to achieve such positive effects, learning factory courses and modules need to consider success factors of learning itself (Tisch and Metternich 2017, pp. 90–92). For success factors of learning and experiential learning in specific see sections 2.3.2 and 2.3.3.

Table 15 links success factors of learning processes and corresponding potentials of learning factories.

Table 15: Potentials of learning factories as learning environments to enhance competence development (based on Tisch and Metternich 2017, pp. 90–92)

Success factors to enhance learning processes (incl. exemplary literature reference)	**Potentials of learning factories as learning environments**
Contextualization, situated context and authentic environment (e.g. *Jonassen 1999; Lave and Wenger 2011;Caine and Caine 1990*)	Partial model of real factory provides a rich learning and authentic learning context
Activation of learners - including emotions and senses (*Johnson et al. 2006; Bonwell and Eison 1991; Caine and Caine 1990*)	Generation and application of knowledge in the learning factory (learner active phases) using own ideas
Problem solving (e.g. *Boud and Feletti 2003*)	Solving of real problem situations in the learning factory as authentic learning environment
Motivation (e.g. *Deci et al. 1991*)	Motivation by the reality character and the possibility to act hands-on immediately
Collectivization and social activities (e.g. *Greeno et al. 1996*; *Caine and Caine 1990*)	Self-organized learning in groups is a suitable model in learning factories
Integrate thinking and doing (e.g. *Aebli 1994*)	Alternation of hand-on phases in the learning factory and systematization phases
Self-regulated (e.g. *Schunk 1990),* and self-direction *(*e.g. *Garrison 1997)*	External and self-controlled learning processes are enabled – depending on the prerequisites

In addition, literature points out following positive effects of learning factories: emphasis on teamwork, social interactions and soft skills (Hambach et al. 2016, p. 234, Martawijaya 2012, p. 52) as well as the interdisciplinary applicability of the concept (Jäger et al. 2013, p. 1; Kreimeier et al. 2014, p. 187; Nöhring et al. 2015, p. 114 Rentzos et al. 2014, p. 193).

2.4.4 Competence development at learning factories

In their overview on learning factories *Abele et al. 2019* summarized learning factory research concerning competences addressed in learning factory courses based on *Müller-Frommeyer et al. 2017*. The authors clustered learning factory associated competences to the competence classes proposed by *Erpenbeck and Rosenstiel 2003* (see section 2.3.1). This results in relative context independent competences and in domain and context specific competences (Abele et al. 2019, p. 32). Table 16 shows an extract of the identified context independent competencies to give an impression of the scope of learning factories in competence building. Further information can be retrieved in *Abele et al. 2019* and the cited literature references.

Table 16: Context independent competences addressed in learning factories
(extract - adapted from: Abele et al. 2019, pp. 33–35)

Competence classes	**Competences**	**References (selection)**
Professional and methodological	(Application of) professional knowledge	*Cachay et al. 2012; Blume et al. 2015; Steffen et al. 2012; Müller-Frommeyer et al. 2017*
	Interdisciplinary knowledge and understanding	*Jäger et al. 2013; Lamancusa et al. 2008; Jorgensen et al. 1997*
	Project management	*Blume et al. 2015*
	Further: - Presentation skills, - Analytical thinking - Domain specific competences[8]	For further references see *Abele et al. 2019, p. 33*
Socio-communicative	Adaptability	*Wagner et al. 2012b*
	Capability to work in teams	*Blume et al. 2015; Goerke et al. 2015; Gräßler et al. 2016*
	Communication skills	*Müller-Frommeyer et al. 2017; Blume et al. 2015; Jorgensen et al. 1997*
	Further: - Problem solving capability - Leadership	For further references see *Abele et al. 2019, p. 34*
Personal	Creativity	*Abele et al. 2015b; Blume et al. 2015*
	Motivation	*Blume et al. 2015; Dinkelmann et al. 2014; Tisch et al. 2013*
	System thinking capability	*Kreimeier et al. 2014; Blume et al. 2015; Goerke et al. 2015*
	Further: - Personal responsibility - Result-oriented action - Reflexion capability - Technology affinity - Openness	For further references see *Abele et al. 2019, p. 35*
Activity and action	Innovative capability	*Balve and Albert 2015; Blume et al. 2015; Jäger et al. 2013*
	Decision-making	*Blume et al. 2015; Goerke et al. 2015*
	Planning and realization capability	*Nöhring et al. 2015*

However, according to *Abele et al. 2019*, especially the development of domain specific competences ('professional and methodological competences' - see Table 15) are *"[…] in general the primary goals of learning factory courses."* (Abele et al. 2019, p. 32) Table 17 presents selected domains and related competencies addressed in learning factories. Further, Table 17 lists exemplary learning factories focusing on the described domains.

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[8] See Table 17

Table 17: Selected domains, exemplary related competences and learning factories (extended from: Abele et al. 2019, 37-38 & 200–213)

Selected domains	**Domain specific competences**	**References (exemplary)**	**Selected learning factories with domain focus**	**References (exemplary)**
Lean	- Ability to perform systematic problem solving - Ability to map and design value streams - Ability to implement flow lines in production systems	*Reiner 2009; Cachay and Abele 2012; Kreimeier et al. 2014*	Process learning factory CiP	*Reiner 2009*
			IFA-Learning Factory	*Seitz et al. 2019*
			LEAD Factory	*Micheu and Kleindienst 2014*
Industry 4.0 / Digitalization	- Use of innovative technologies - Ability to plan implementation processes of industry 4.0 applications - Design digital applications for production systems	*Küsters 2018; Hulla et al. 2019a; Erol et al. 2016*	AAU Smart Production Laboratory	*Madsen and Møller 2017*
			LEAD Factory	*Karre et al. 2017*
			Learning Factory for Global Production	*Lanza et al. 2019*
Resource & energy efficiency	- Analysis of energy flows - Designing energy-efficient production systems - Energetic optimization of machine tools	*Abele et al. 2016; Kreitlein et al. 2015; Blume et al. 2015*	ETA-Factory	*Abele et al. 2016*
			LPS Learning Factory	*Prinz and Kreimeier 2019*
			Die Lernfabrik	*Blume et al. 2015*
Industrial engineering	- Analysis of ergonomic workplaces - Application of design for manufacturability - Planning of technology and production processes	*Dinkelmann et al. 2011; Jäger et al. 2013; Morlock et al. 2017*	Industrial Engineering Laboratory	Steffen et al. 2012
			aIE Learning Factory	*Dinkelmann et al. 2011*
			Micromanu	*Morlock et al. 2017*
Product development	- Product design - Coordination of product development and production - Management of change requests	*ElMaraghy and ElMaraghy 2015; Bender et al. 2015; Schützer et al. 2017*	Bernand M. Gordon Learning Factory	Lamancusa et al. 1997
			Product Development Process Learning Factory	*Schützer et al. 2017*
			iFactory, iDesign, iPlan	*ElMaraghy 2019*
Changeability	- Creation and improvement of changeable production systems - Potentials of the digital factory for fast and efficient turbulence management - Identifying and dealing with changing effects on the product and the manufacturing system	*Riffelmacher 2013; Matt et al. 2014*	aIE Learning Factory	*Riffelmacher 2013;*
			iFactory, iDesign, iPlan	*ElMaraghy 2019*
			Pilot Factory Industrie 4.0	*Sihn et al. 2019*

A recent survey performed by *Sudhoff et al. 2020* identified that current learning factories primarily address the areas of direct production (manufacturing, assembly and logistics). Downstream activities such as service are of secondary importance. Upstream topics such as production network or supply chain related topics are not stated at all. Further, the authors identified the most addressed domains for teaching at learning factories. The top-five domains are: (1) improvement of production processes; (2) digitalization; (3) production management; (4) automation; and (5) factory planning. (Sudhoff et al. 2020, p. 118)

Figure 28 shows the typical focus of learning factory concepts.

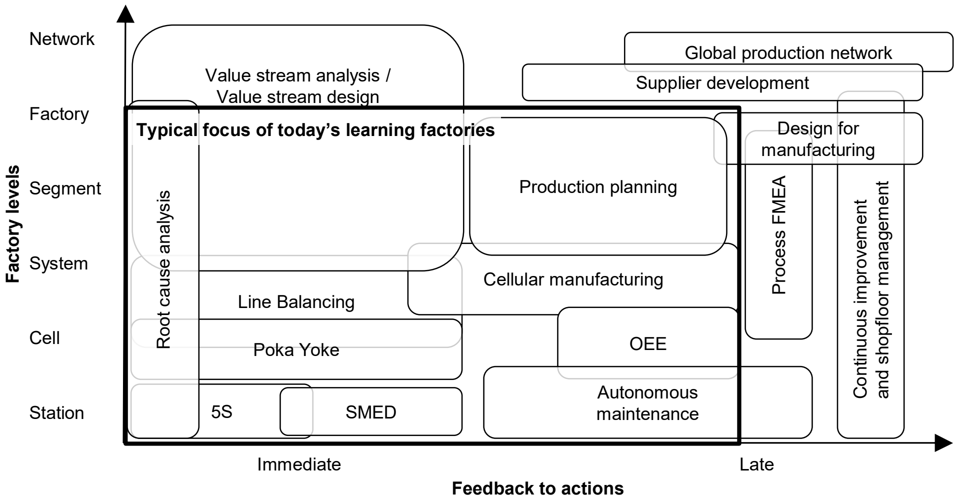

Figure 28: Focus of current learning factory concepts (Abele et al. 2019, p. 288)

2.4.5 Limitations of learning factories

However, in order to take advantage of the full potential of learning factories for competence development challenges of actual concepts are: (1) resources; (2) mapping ability; (3) scalability; (4) mobility; and (5) effectiveness (Tisch and Metternich 2017, p. 94). Table 18 describes these challenges in more detail.

Table 18: Limitations and effects of learning factory approaches
(based on Tisch and Metternich 2017, pp. 93–94; Abele et al. 2019, p. 287)

Current limitations for learning factories	Effects of limitations on learning factories	Selected solution approaches
Resources	The development of a learning factory concept and its implementation is resource intensive. Crucial resources are amongst others monetary resources, space, personnel for the development and operation, equipment and a sustainable operation model.	Digital and virtual learning factories, Mini and low cost learning factories, integration of ICT-equipment
Mapping ability	Learning factory approaches intent to address issues on all factory levels (from production networks to single workplaces). However, a single learning factory is limited as an image of a real factory. The mapping ability contains content-, solution-, space-, and time related challenges.	Networks of learning factories, digital and virtual learning factories, integration of ICT-equipment
Scalability	In comparison to other learning concepts (e.g. frontal lecture), the learning factory is limited concerning the number of participants (mostly limited up to 16 participants). Further, the support effort of faculty personnel is higher as well.	Distance learning and blended learning
Mobility	Learning factories are in general bound to their original location.	Digital and virtual learning factories, Mini and low cost learning factories, integration of ICT-equipment
Effectiveness	Even though that competence building is the common main goal of learning factory approaches its effectiveness is rarely evaluated. The focus during the development phase is often put on infrastructure and equipment whereas the design of effective didactical approved concepts lacks.	Innovative media approaches, systematic learning factory design approaches, methods for learning/ competence assessments

As mentioned above, *Abele et al. 2017* provided an in depth literature review about learning factories. The authors identify in general a research need to overcome the described limitations of learning factory concepts. Amongst others, the authors emphasize research regarding the combination of physical and digital or virtual concepts. Each of these concepts offers specific advantages and the integration into a hybrid learning factory seems beneficial. Research should therefore prioritize how these concepts collaborate and how to enhance knowledge transfer. Further, research to overcome the limited mapping ability and resource limitations in order to include new learning content using the potentials of learning factory environments is needed (Abele et al. 2017, p. 821).

In the attempt to give a comprehensive overview of the subject of ‘learning factories’ with the most effort so far, *Abele et al. 2019* strengthen individual points mentioned above yet again. The authors conclude that due to the increasing speed of change of production systems in industry, learning factories must be able to include new approaches and technologies to enhance future production environments. Further, the authors stress the integration of ICT, simulations and virtual environments into learning factory concepts to enable an expansion of the current content and to address the development of related competences. Thus, the authors highlight the research need to establish hybrid learning environments for training and education. This includes research about the general inclusion of digital elements and related interfaces between physical environment and digital content. (Abele et al. 2019, pp. 455–456)

2.4.6 Summary: Learning factories

This research considers the definition of 'learning factory' according to *Abele 2018. A* learning factory comprises following aspects: (1) authentic processes with several working stations and organizational as well as technical aspects; (2) a close-to-reality abstraction of real value chains with a changeable on-site setting; (3) physical processed product(s); and (4) a didactical concept to enable learning by participant's own actions within the learning environment.

As constructivist learning environment learning factories enable an alternation of understanding, cognition, application and reflection processes to enhance learning in domain specific contexts. Further, learning factories are used in research as 'research enabler' and 'research object' as well as technology demonstrator for innovation transfer. However, the common objective of learning factories is competence development and more precise, mostly domain specific competence development. Learning factory trainings are used to qualify students and industrial personnel at all company levels – from shopfloor to top-management. Due to the limit of available time for such trainings in industry, there is a need for rapid knowledge transfer. Thus, pre-structured learning processes are necessary. In learning factories this is enabled through clear didactical concepts and at least two different learning factory setups for the intended learning objectives. First, participants experience a suboptimal setup with open issues to identify; reflect; and address as well as the possibility to improve. Second, a defined target setup, which should be achieved by the use of the learning content by the participants, exists. Therefore learning factory infrastructure needs to be versatile and flexible to enable direct change and improvements by participants throughout trainings.

To address topics from factory- to workplace level learning factory setups need to include such two setups on each level so that participants get the opportunity to experience improvements and change on targeted factory levels. However, most learning factories focus on areas of direct (shopfloor-) production (manufacturing, assembly and intralogistics). Further, a recent survey performed by *Sudhoff et al. 2020* shows that downstream activities (service, maintenance, etc.) and upstream activities (supply chain, inbound logistics, etc.) are of secondary importance. This goes partly along with the research need to overcome limitations such as the mapping ability (content, object, space, cost and time related mapping abilities) and needed resources of learning factories. Potentials future research might consider are so-called 'hybrid learning factories' combining the physical environment and digital content to overcome the mentioned limitations.

Nevertheless, the learning factory concept offers potentials to enhance competence development by implementing success factors of learning processes such as 'motivation', 'contextualization' or 'alternation of thinking and doing' within courses. Therefore, literature highlights the necessity of a structured approach for developing learning factory based courses taking into account didactical as well as infrastructural considerations.

Table 19: Key take-aways and delimitation of 'learning factories' concerning this research

Key take-aways	Delimitation
- Learning factories are constructivist learning environments supporting competence building regarding context-independent and domain specific competences and enhance participants learning - Learning factories aim in general to develop competences for all factory levels - Besides close-to-reality technical infrastructure to enable authentic experiences there is the clear need of a didactical concept - For designing a learning factory course potentials to enhance participants learning need to be addressed - A structured approach for developing a training course is needed - Training courses for industry have just a short timeframe and therefore require rapid knowledge transfer of the course content through well-designed, pre-structured learning processes	INCLUDES: - Extension of existing learning factory for the topic of agile operations which is not addressed in current practice - The requirement of an existing procedure model to develop a competence based learning factory course for agile operations - Contribution to learning factory literature concerning the mapping ability for strategic aspects and incorporation of upstream and downstream activities as potentially necessary to cover the topic of agile operations EXCLUDES: - Development of a structured guiding framework to design learning factories or teaching modules - Development of a new learning factory (environment, products, processes, etc.)

2.5 Review of related studies within the research field of learning factories

This chapter reviews research with particular relevance for the present work in more detail. First, related research with a similar scope as the present work is outlined. Second, guiding frameworks to design learning factory training courses are reviewed. The target of this section is to gain insights into related research in order to apply learnings in the empirical part of the present thesis at hand.

2.5.1 Operations management topics in learning factories

This section reviews selected studies with a similar scope within the subject of 'learning factories'. As no research could be found in literature addressing the topic of 'agile operations' within learning factories, research projects with the aim to include operations management topics to learning factories in general are reviewed. Further, emphasize is put on research work with a specific focus on 'changeability' due to partly shared objectives with the concept of agility. The objective of this review is to gain a solid understanding of (1) challenges and developed solution approaches to learning factory limitations; (2) the applied guiding framework (further addressed in section 2.5.2) and (3) the applied evaluation approaches.

Reiner 2009 describes within his thesis a **method for a competence-oriented lean transformation** (translated from German). The aim of this research is to develop a holistic and standardized concept for employee qualification, as competences are success factors of lean production. The author describes the concept 'learning factory' as 'instrument' for efficient competence development. Further, the author points out that conception and implementation of a learning factory are highly complex and therefore devotes a main part of his research work to this topic. However, the author does not apply a dedicated guiding framework for the design of the learning environment and the didactical concept. Nevertheless, the developed learning factory approach shows a high degree of depth concerning infrastructural and didactical considerations. Basis for the developed learning factory are defined competences. The author starts with the derivation of requirements from lean production methods on the production system and the product processed in the learning factory. Based on these requirements the author choses products and the learning factory infrastructure. The learning factory principle using different pre-defined maturity levels is applied. The research describes the didactical concept in detail using standardized documentation of learning situations for different lean production methods. As in reality operational improvements are linked to concrete corporate objectives, the research work further includes a fictional corporate case study. The evaluation of the learning factory concept does not consider the evaluation of the competence development. However, the author states that interviews with representatives from science and industry prove the value of the method and the interest in adapting the method to other functions and industries.

In his doctoral thesis '**Conception of a learning factory for multi-variant assembly**' (translated from German) *Riffelmacher 2013* aims to develop a qualification concept for advanced industrial engineering within a learning factory setting. The overall objective is the conception of a learning factory for multi-variant assembly showing possible solutions for coping with turbulences. This is done through the combination of existing potentials of the digital factory and changeable production systems (see chapter 2.2). The focus is limited to changeability on production system and workplace level. For the didactical development of the qualification concept the author followed the approach developed by *Bonz 2009* building up onto six decision levels (overall concept, forms of action, social forms, articulation, teaching concepts and media) (Bonz 2009, p. 23).

Based on this approach the author clusters his teaching course as follows: (1) reactivation of basics; (2) teaching of new methods; and (3) independent application within the learning factory. For the reactivation of basics, learners are provided with basic knowledge of industrial engineering via e-learning, theoretical input and exercises. The transfer of the new methods and tools of advanced industrial engineering starts with a theoretical explanation (frontal lecture) followed by exemplary showing methods to participants, application on a well-defined practical example and self-directed learning by participants. Finally, the independent application in the learning factory is carried out within the framework of a round based and scenario driven approach. The participants plan the implementation in a digital environment before realizing these planning results in the physical learning environment.

The research work then introduces the considerations developing the digital (planning) and physical learning environment based on the didactical concept. First, the digital environment is derived based upon methods for operations planning including process, capacity and layout planning as well as logistical dimensioning and detailed production planning. Second, the author develops the physical learning environment structured according to the organizational, technical, spatial and product requirements of the multi-variant assembly. To achieve a bidirectional data exchange the digital planning environment and the changeable assembly system are coupled. The author describes learning situations based on three characteristics: (1) procedure; (2) methods; and (3) supporting resources. Further, the author tests the qualification concept at the developed learning environment with participants from industry. This is done with an immediate validation directly after completion of the respective learning module and an indirect validation six months after completion of the entire training. The author measures learning outcomes through a questionnaire based on the self-perception of participants (see Table 6).

Faatz 2017 describes in her doctoral thesis '**Competence development in tool management within the framework of a learning factory: development and testing of a computer-aided simulation game**' (translated from German) the development of competences to design a tool supply system within manufacturing. This approach overcomes the time-related learning factory limitation (see section 2.4.5). For an authentic reproduction of the characteristics of tool supply, it is necessary to consider e.g. machine parameters or the varying operating times due to workpiece characteristics (form, material, etc.). The learning environment must therefore be designed in such a way that the problem situation can be shortened in time. In order to consider multiple aspects of didactics and teaching infrastructure the author reviews procedure models to develop the intended learning module of tool management. The author includes procedure models considering learning goals, learning contents, design of teaching-learning arrangements, intended learning processes, media and evaluation approach. Further, the author additionally assesses whether procedure models focus on competence-oriented learning objective formulation. The chosen model of *Abel et al. 2013* considers learning situation planning according to the framework of *Tenberg 2011* (systematization, exploration/experimentation, reflection evaluation – see

Table 10). The chosen procedure model emphasis both types of learning processes – information assimilation and the experiential learning process (see section 2.4.2). The author formulates based on literature the underlying 'professional and methodological' (Erpenbeck and Rosenstiel 2003) competence: *"The participants have the ability to design an efficient and company-specific tool supply system for small and serial production."* (Faatz 2017, p. 88) This competence is further broken down into sub-competences and its consisting elements (see section 2.3.1). Based upon these information the author derives the order of activities, the in detail design of these activities (media, materials, teaching methods, interactions, etc.) and in parallel the design of the learning environment. A simulation as learning environment enables participants to experience the effects of their decisions immediately. Therefore, based on an event-discrete simulation (software: 'Tecnomatix Plant Simulation') the author elaborates a business game based on a procedure model proposed by *van der Zee et al. 2012*. This framework consists of following consecutive phases: (1) understanding the learning situation; (2) determination of learning objectives; (3) identification of model output; (4) identification of model input; and (5) determination of model content – scope and level of detail. The resulting business game starts with an analysis of the initial situation and targets. Then, participants plan and chose measurements within the simulation environment and start the simulation. Through observations of the simulation animations and evaluation of key performance indicators (KPIs), participants reflect the success of implemented measures. This play process is repeated throughout the learning module. However, there is no interaction of participants with the physical learning environment nor any relation in-between the business game and physical production system. Concerning evaluation of the learning module the author applies a pre- post knowledge test, peer observation, intermediate course results and participant surveys.

Küsters 2018 describes in his research a **methodology for developing a learning factory for the digital transformation of production** (translated from German). Further, the author describes the operating system of such a learning factory. The overall objectives are (1) the design of a learning factory concept for the systematic development of competencies in the context of the digital transformation of production; (2) the development of a comprehensive methodology for the targeted construction and economic operation of such a learning factory; and (3) the implementation of the methodology using examples. The developed methodology for the development and construction of the intended learning factory concept consists of these five phases (for more details see section 2.5.2). The developed learning factory concept is based upon self-formulated competences divided into three areas (use cases, technological basics and implementation competence). The learning modules (activities, media, etc.) are described only exemplary in the course of the research work. However, in addition to the physical learning environment (product, processes, etc.), the author describes the need to show participants the impact of digital transformations on the overall goal of increasing profitability at the corporate level. Therefore, the author proposes the development of a fictional case study describing the corporate situation involving the physical learning factory processes and products. The proposed case study information include amongst others the company history; product segments; overview of production sites; basic production KPIs; or sales volume. Further, the developed concept foresees dedicated employees to operate the learning factory infrastructure throughout training courses (and not the participants themselves). In order to explain their role in all configuration stages of the process chain and to provide the participants with the relevant information for the respective learning module, the employees need a comprehensive understanding of their respective role. Therefore, so-called 'role-cards' provide in detail descriptions concerning the concrete tasks, additional information (e.g. age, character) and typical questions from participants with respective answers. The author applies and tests the elaborated methodology for the development and operation of a learning factory for digital transformation in production in two use cases.

In the following selected research papers addressing the concept of changeability in learning factories are introduced.

Pasek et al. 2004 present in their research a graduate course of '**Agile, Reconfigurable Manufacturing**'. The course is based upon technical and business issues for mass customization in manufacturing. Throughout a long-term project student teams explore core topics of product development, manufacturing and business practices. Throughout the course participants have the opportunity to visit the Integrated Manufacturing Systems Laboratory at the University of Michigan and get to know typical factory equipment. Reviewing the industrial manufacturing architectures participants discuss possibilities of adapting to changes (product mix, product type) on production system level. (Pasek et al. 2004, pp. 742–752)

Dinkelmann et al. 2011 describe the **transformable assembly system 'iTRAME'** at the IFF Stuttgart and **advanced industrial engineering training**. This research is a previous interim result of the doctoral thesis of *Riffelmacher 2013* (see above). The 'iTRAME' learning factory infrastructure is based upon a FESTO Didactic platform. Participants plan for short-term interruptions (e.g. machine failure) and middle-term (e.g. product mix) changes. This includes planning of material and information flow as well as new production layouts. In a production run participants test their planned solution where a machine failure is simulated and short-term solutions need to be carried out. Finally, production is resumed and results are discussed in terms of productivity and personal assessment of how well the planned system has worked. As this research was published, the finally integrated digital planning environment (see *Riffelmacher 2013*) was not yet build up (Dinkelmann et al. 2011, pp. 626–629).

ElMaraghy et al. 2012 describe in '**Change in manufacturing—Research and industrial challenges**' the 'iFactory' at the University of Windsor, Canada. This transformable learning factory is based upon a FESTO didactic platform similar to the learning factory at the IFF Stuttgart. In addition, the concept comprises intelligent interactive design ('iDesign') and a planning environment ('iPlan'). The production system consists of assembly modules and inspection stations. The configuration of the single elements of the production system can be reconfigured due to standardized interfaces (e.g. mechanical, electrical, etc.). Focus in research relies on managing product variants, changeable production enablers, product and systems design innovation and reducing complexity of manufacturing and assembly systems. (ElMaraghy et al. 2012, pp. 2–4)

A **concept for a learning factory for changeability** is introduced by *Gossmann and Nyhuis 2012*. Changeability is seen by the researchers as ability to change outside available flexibility corridors on production system level. The areas of influence on the production system are human resources, organization, technology and logistics. The elaborated concept is based on an underlying procedure for the implementation/activation of changeability. The didactical concept is build upon the alternation of a 'production phase' and an 'evaluation phase'. This alternation is done in three main cycles: (1) utilization of flexibility; (2) activation of changeability; and (3) design of changeability. Throughout this cycles participants are confronted with external change drivers, identifying change bottlenecks and the elaboration of plans to adapt the production system. The outcome of the course was measured with a survey showing the impact on mainly context independent competences/competence classes (see section 2.3.1). (Gossmann and Nyhuis 2012, pp. 2185–2189)

In their research *Andersen et al. 2019* describe a **course on changeability within the learning factory at Aalborg University**. This learning factory represents a modular and reconfigurable manufacturing system build upon a FESTO didactic platform (for more information see *Madsen and Møller 2017*). The course is organized as student project with 140 hours of project work ('problem-based learning'). The objective of the course is to teach the topics of (1) product development; (2) design and operation of the manufacturing system; and (3) business model development as well as cross-functional synergies of these three domains. Students analyze the manufacturing system of the learning factory concerning changeability (e.g. product family extension, demand increase) on production system and workstation level. Further, participants establish different system configurations. Student feedback indicates that the learning factory supports the theoretical knowledge transfer.

In addition to the identified and reviewed studies concerning changeable manufacturing Wagner et al. emphasize learning factories as important source for training to develop changeable production systems as learning factories are "*[…] capable to cope with the dynamic requirements demanded by the global market.*" (Wagner et al. 2015, p. 157)

Table 20 summarizes key aspects and remarks concerning the introduced research work with a similar scope as the present doctoral thesis.

Table 20: Summary of selected related studies

Author	**Key aspects**	**Remarks**
Reiner 2009	- Learning factory as instrument for efficient competence development - Competences for lean production formulated - Learning factory concept derived from requirements of lean production methods - Fictional case study links operational improvements to corporate objectives	- No sources for developed competence profiles - No validation regarding the intended competence development
Riffelmacher 2013	- Development of a qualification concept for advanced industrial engineering within a learning factory setting - Didactical concept development is based on guiding framework (*Bonz 2009*) - Digital environment for planning activities and physical learning environment are coupled - The participants are confronted with new problem situations via scenario-based learning	- Focus is limited to production system and workplace level - No competences are formulated - Concept focuses on the 'information assimilation' process of learning - Self-perception of participants as assessment method
Faatz 2017	- Competence development in tool management within a learning factory setup - Simulation environment enables to overcome mapping limitation (time) - Development of learning modules based on a guiding framework - Application of different evaluation methods to evaluate the applicability of developed course elements and the learning outcome itself	- Competences formulated based on literature - No interaction of participants with the physical learning environment in place - No relation or connection in-between the simulation environment and the physical learning factory - Evaluation based on different methods providing more detailed information
Küsters 2018	- Development of a methodology for a learning factory concept for the digital transformation of production - Competence profiles are formulated - Fictional case study links operational improvements to corporate objectives - Dedicated roles of workers within the learning factory implemented to improve authenticity	- No sources for developed competence profiles - No validation of the intended competence development
Pasek et al. 2004	- Course concept for technical and business issues for mass customization - Manufacturing systems laboratory used as demonstration facility of manufacturing infrastructure	- No hands-on activities at the learning environment - Long-term project (not suitable for industrial employees) - No evaluation of learning outcomes
Dinkelmann et al. 2011	- Course concept for advanced industrial engineering - Learning factory consists of a transformable assembly system based on a FESTO didactic platform - Planning phase and production run with simulated interruptions/changes (e.g. machine failure) - Results of participants actions are discussed based on productivity and subjective assessment	- Previous interim result of the doctoral thesis of *Riffelmacher 2013* - Focus is limited on production system and workplace level - No evaluation of learning outcomes
ElMaraghy et al. 2012	- Description of the changeable learning factory concept ('iFactory') based on a FESTO didactic platform	- No information about implementing changeability in training courses
Gossmann and Nyhuis 2012	- Design of a learning factory course for changeability - Alternation of 'production phases' where participants experience change and 'evaluation phases' where changeability is created - Participants survey concerning developed competences - based on mainly context independent competences	- Focus is limited on production system level - Underlying procedure to develop changeability for participants to follow throughout the course - No remarks on the learning environment itself (e.g. processed products, infrastructure, etc.)
Andersen et al. 2019	- Course concept for changeability within a learning factory - Learning factory build upon a FESTO didactic platform - Integrated topics: product development, design and operation of manufacturing system and business model development	- Long-term project – 10% of course duration are planned for learning factory activities - Student feedback indicates suitability of learning factory environment

2.5.2 Procedures to develop learning factory courses

As described in chapter 2.4, learning factory concepts need to answer following question: "*Who should learn what, from whom, when, with whom, where, how, with what and for which purpose?*" (Zierer and Seel 2012, p. 2). Further, as learning factories are complex systems literature emphasizes the need for a guiding framework for the development of learning factories and respective didactical concepts in order to ensure an efficient gain of competences (e.g. Cachay and Abele 2012, pp. 642–643; Tisch et al. 2016, p. 1358). Therefore, in the following selected guiding frameworks for the development of learning factories (and courses) are reviewed.

Based on consulted literature following criteria of guiding frameworks are taken into account for chosing a framework as basis for the empirical part of this research study:

- Based on instructional design / didactics literature
- Based on the concept of competence
- Structured, step-by-step approach
- Level of detail concerning supporting tools/methods and concept (e.g. learning factory infrastructure)
- Applicability and feasibility in regard to this research study

As previously described, ***Reiner 2009*** presents within his doctoral thesis the development of a learning factory for competence development concerning lean production. The author developed the corresponding learning factory based on an individual chain of argumentation. First, a suitable product is chosen based on formulated competence profiles and lean methods. Then, the value stream configuration and logistic processes for the learning infrastructure are defined. Based on these results and competence profiles the didactical concept as well as organizational and steering processes are elaborated. Finally, the learning environment is embedded in a case study to link shopfloor improvements to (financial) corporate objectives. Further, the author describes the operation phase of the learning factory. Concerning the evaluation of the suitability of the derived learning factory concept the author refers to discussions about the impact of the developed concept with industry representatives and to a 2-year usage phase. However, the applied approach for the development of the learning factory and related trainings itself was not evaluated specifically. (Reiner 2009, pp. 86–124).

Similar to *Reiner 2009* the doctoral thesis of ***Riffelmacher 2013*** ('Conception of a learning factory for multi-variant assembly' – see previous section) introduces a process based on an individual chain of argumentation. In contrast, the didactical concept development for the intended qualification concept for advanced industrial engineering is based on the decision levels according to *Bonz 2009* (see Figure 29). The conception of the physical learning factory is based on requirements derived by the author from advanced industrial engineering planning methods. These requirements can be broken down into the following subsections: (1) Requirements from the planning tasks (organizational, technical, and spatial); (2) Requirements from the production program; and (3) requirements for the adaptability of the learning infrastructure. In addition, these requirements are considered for the selection of a suitable product. The applied approach does not describe an evaluation step. However, the author conducted trainings with industry to evaluate the developed approach using participants interviews and questionnaire based on self-perception of training contents. (Riffelmacher 2013, pp. 132–141)

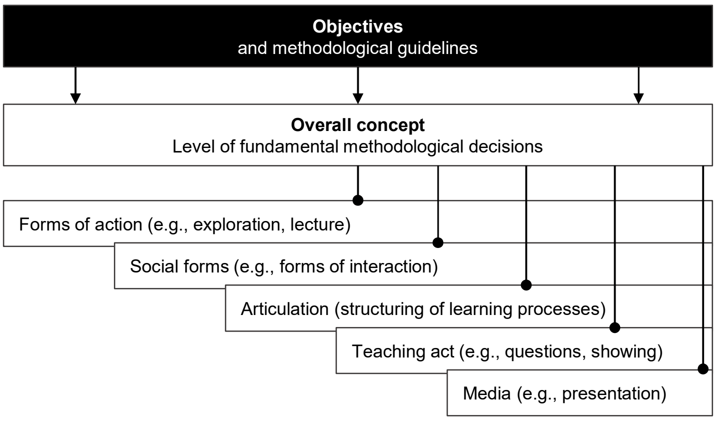

Figure 29: Decision levels for the conception of a qualification program
(adapted from Bonz 2009, p. 23)

The author Michael Tisch (together with alternating co-authors) published guiding frameworks - partly built-on each other - for the competence-oriented design of learning factories throughout the years 2013 to 2018 (see *Tisch et al. 2013; Tisch et al. 2016; Tisch 2018*). The hereinafter referred to model from ***Tisch 2018*** consists of three design levels: (1) macro – learning factory level; (2) meso – teaching module level; and (3) micro – learning situation level and is developed especially for the subject of lean production. For each design level two didactic transformations are addressed. The first didactic transformation defines relevant learning objectives. The second didactic transformation defines how the relevant learning objectives are addressed within the learning factory setting. Further, each of the three design levels is based on formulated competences. The macro level addresses the general target definition of the learning factory, learning objectives, the conceptual and detailed design of the learning factory infrastructure as well as modularization and program definition. The meso level derives requirements and boundary conditions on learning module level. Learning objectives are detailed and the technical and the methodological design of learning modules takes place. On the micro level follows a further detailing of boundary conditions, requirements and objectives for each learning situation. Finally, the actual design of the planned learning situation takes place. However, the proposed methodology includes several feedback loops within and across the design levels. The authors proposes for each step of his methodology relevant methods and tools. In addition, the author emphasize the validation of the intended competence development within the proposed methodology. (Tisch 2018, pp. 107-160)

The developed methodology was applied in two use cases and the effectiveness is discussed with involved experts (Tisch 2018, pp. 193-195).

Figure 30 illustrates the three design levels with a brief description of addressed issues.

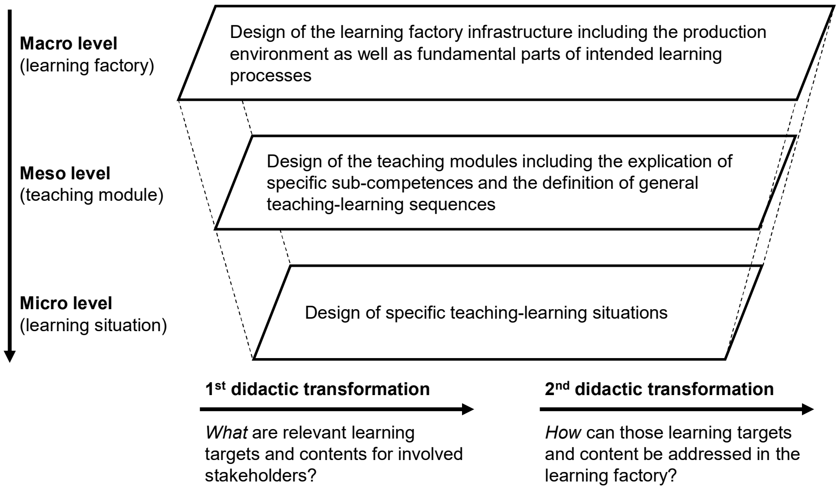

Figure 30: Three design levels with respective decision scope (Tisch et al. 2016, p. 1360)

Doch et al. 2015 describe in their research a generic three-phase approach for the development of a learning factory (see Figure 31). Phase 1 ‘requirement analysis’ contains the analysis of industrial value streams, limitation of the considered value stream area, the abstraction of the real process for the learning factory, an analysis of intended competences and the derivation of needed infrastructure. Phase 2 ‘conception’ elaborates teaching modules and teaching methods. The last phase ‘final design and implementation’ concretize content- and methodological elements of teaching methods, a quality assessment (e.g. pre-test with experts), operation and continuous improvement of the learning factory. The developed methodology was used to develop a learning factory for lean management in the pharmaceutical industry. (Doch et al. 2015, pp. 26-30)

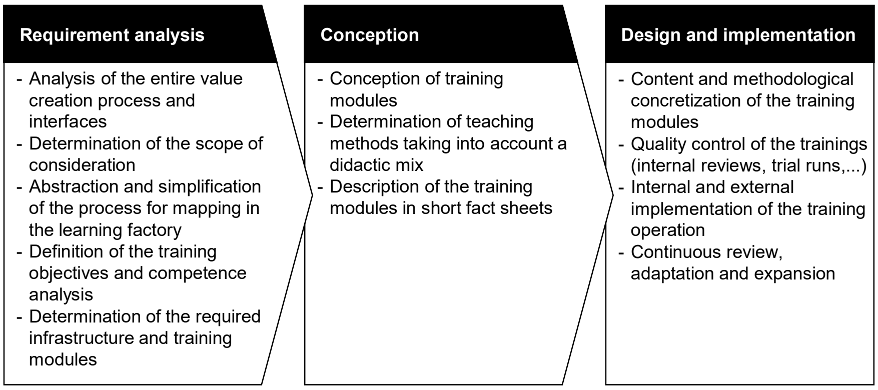

Figure 31: 3-Steps learning factory development methodology (Doch et al. 2015, p. 28)

Based on a review of existing learning approaches ***Plorin et al. 2015*** derived a regulatory framework for designing learning environments and a corresponding didactic approach. This 8-step framework (see Figure 32) is supported by underlying methods to enable a process-oriented quality control. The proposed model consists of the following eight steps: (1) framework characterization of existing learning environment; (2) use case identification; (3) formulation of learning modules; (4) linking learning modules to learning environment competences; (5) structure competence profiles of target groups; (6) structure of content and dependencies of learning modules; (7) design of the learning environment; and (8) the integration into the existing learning environment. In addition, the authors address continuous improvement of the didactical and infrastructural concept and training evaluation as measurements of the effectiveness. The developed model was applied in two use cases concerning learning factory training courses. (Plorin et al. 2015, pp. 16–17)

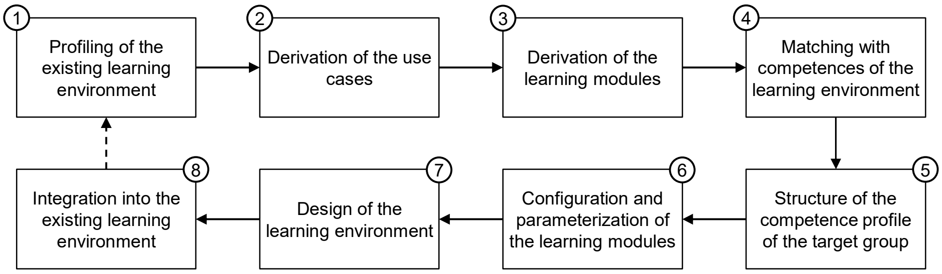

Figure 32: Regulatory framework for designing learning factory environments
(Plorin et al. 2015, p. 14)

As described above, *Küsters 2018* elaborated a methodology for developing a learning factory for the digital transformation of production. This methodology is separated into five work packages: (1) target setting and requirement derivation; (2) course content; (3) learning factory infrastructure; (4) location and building; and (5) organization and economic viability. These phases are further detailed into eleven steps that are performed partly in parallel or in an iterative manner (see Figure 33). Work package 1 defines targets and requirements concerning the learning factory from the viewpoint of the facility operator, the planned service offer and the target group. In work package 2, a corporate case study and learning modules are elaborated. Throughout work package 3 the two different maturity setups (suboptimal as-is maturity level vs. optimized to-be maturity level – see chapter 2.4.2) including learning factory product, value stream design, production layout, material and information flow, workplace design and organizational aspects are defined in an iterative manner. Work package 4 addresses the issues of defining a location and a building for the learning factory. Work package 5 includes the development of the operating model, the operational team and the preparation of a financial plan. Further, the author provides a chronological sequence for these steps over five development phases of a learning factory implementation project. Furthermore, the research work introduces partly methods, tools and templates for individual steps. The author applies the elaborated methodology for the development and operation of a learning factory for digital transformation in production in two use cases.

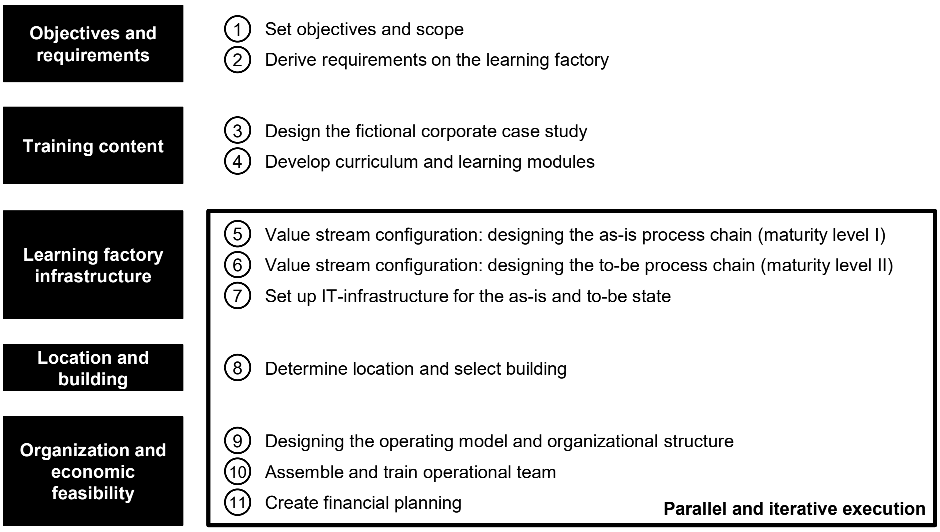

Figure 33: Methodology for the development of a learning factory for digital transformation in production (Küsters 2018, p. 126)

Table 21 summarizes the introduced guiding frameworks including remarks concerning key aspects and the relevance for the present work.

Table 21: Summary of selected guiding frameworks for the development of learning factories (extended from Abele et al. 2019)

Author	**Design Object**	**Key aspects**	**Remarks**
Reiner 2009	Learning factory	- Five step approach for the development of a learning factory for lean production - Competence based	- Not based on didactic/instructional design literature - No guiding framework derived - No recommendation for supporting tools/methods
Riffelmacher 2013	Digital and physical learning environment	- Development of a learning factory for high-variant assembly systems - Based on didactic/instructional design literature (*Bonz 2009*) - Development based on content related planning methods and requirements	- Not based on competences - No guiding framework derived - No recommendation for supporting tools/methods
Tisch et al. 2013; Tisch et al. 2016; Tisch 2018	Learning factory, learning modules and learning situations	- Holistic learning factory design approach on three conceptual levels (learning factory, learning module and learning situation) - Based on didactic/instructional design literature - Detailed framework with corresponding methods and tools for each decision level - Competence based	- Developed throughout several research work throughout the years 2013 to 2018 - Applied by several authors, e.g. *Sadaj 2019, Auberger 2019*
Doch et al. 2015	Learning factory	- Generic three-phase approach for the development of learning factories - Competence based	- Not based on didactic/ instructional design literature - No supporting methods and tools introduced
Plorin et al. 2015	Learning environment / learning modules and learning situations	- Iterative approach for the adjustment of learning environments - Based on didactic/instructional design literature - Competence based - Step-by-step approach	- Explicit applicable for learning factory extensions - Curse/content development builds on defined use-cases
Küsters 2018	Learning factory	- Design approach for learning factories to address digital transformation of production - Competence based - Exemplary introduced methods and tools	Strong focus on the development and operation of the learning factory itself

2.5.3 Discussion of related studies

Reviewed studies show that learning factories support effective competence development for operations management topics such as lean production, tool management, digital transformation in production and changeability.

Developed approaches apply different elements to overcome limitations of learning factories to increase authenticity. This includes fictional corporate case studies to link shopfloor improvements to overall corporate goals, defined roles including responsibilities, challenges of work tasks, etc. within the production system or digital extension of the learning factory. Concerning the digital extensions, *Riffelmacher 2013* links a digital planning environment closely to the physical learning environment. This enables participants to experience the impact of decisions taken at production system level instead of operational improvements like e.g. 5S application. In contrast, *Faatz 2017* developed a simulation game for tool management in order to overcome the time-related mapping limitation of learning factories. However, the simulation developed by *Faatz 2017* is not linked via e.g. the same product family, a joined fictional case study or similar approaches to a physical learning factory.

Introduced research concerning the mapping of the topic 'changeability' within learning factory settings show that taught system improvements are limited to measurements on production system level and workplace level. Further, the identified course approaches are organized as long-term student projects despite the research of *Gossmann and Nyhuis 2012, Dinkelmann et al. 2011* and *Riffelmacher 2013*. However, the latter two of these publications describe the same course concept. Three out of five published concepts rely on a FESTO didactic platform as learning factory infrastructure providing a transformable production system including standardized mechanical and electrical interconnections. The other two publications do not mention the learning factory setup nor do they mention specific requirements for the subject matter of changeability on learning factories.

In general, there is little information about the evaluation of the developed learning factory training courses except the reference to expert discussions or subjective feedback of participants. However, *Faatz 2017* applied a multi-step process to evaluate the elements of the learning factory and to assess the learning outcomes.

The authors of related studies state that the conception and implementation of topics at learning factories is complex. Nevertheless, just one of the reviewed doctoral thesis applied an existing guiding framework for the design of a learning factory concept (see *Faatz 2017*). A majority of the reviewed studies develops the addressed learning factory concept based on an individual chain of argumentation and partly derives a guiding framework. Further, a majority of the considered research works apply the concept of competences as starting point for the development. Yet, there is little information about the derivation of the addressed competences.

Introduced guiding frameworks for the development of learning factory concepts show two classes of depth concerning discussed details of procedure steps and included methods/tools to support the development process. Especially the work published by *Tisch 2018* and *Küsters 2018* introduce methods, tools and templates for various development steps.

Derived from the consulted literature (see chapters 2.3, 2.4 and 2.5) a guiding framework relevant to this research considers instructional design/didactics theory and the concept of competence. Further, besides its applicability and feasibility the framework should provide a structured step-by-step guiding and a high level of detail concering supporting tools and methods. Based on these requirements and the reviewed guiding frameworks, the author of this research chose for the empirical part the guiding framework proposed by *Tisch 2018*.

Table 22: Key take-aways and delimitation of related studies concerning this research

Key take-aways	**Delimitation**
- Learning factories support efficient competence development for various operations management topics - As the development of learning factory concepts is complex a guiding framework supports this process - A multi-step process to evaluate the interaction of theory and learning environment as well as the assessment of learning outcomes is required - The possibility to enhance the physical learning environment through case studies and simulations	INCLUDES: - Guiding framework proposed by *Tisch 2018* - Consideration of introduced approaches to increase authenticity EXCLUDES: - Stand-alone simulation environment - Long-term project as teaching method

2.6 Interim conclusion: Agile operations, the need for experiential learning and potentials of learning factories

This section outlines the author's view on the conducted literature study. It reflects on learnings and forms the basis for the research aim of the present work. The following chapter 3 derives based on this interim conclusion the research aim and questions.

Agile operations

Agile operations is one concept to cope with uncertainties in operations. The scope of agility is seen as guiding framework for decision-making when adapting and deploying an operations strategy. Agile operations is a pro-active approach and considers internal resource reallocation as well as external collaboration across a firm's value chain to gain a competitive advantage. Consequently, agile operations is a multi-dimensional approach comprising activities at various corporate functions. The corporate environment is a main driver for uncertainties and therefore the agility need level as well as the approach itself are individual to each company and vary in time. However, the implementation of agile operations is not limited to a certain type of industry. A key success factor for the implementation of the concept of agile operations is a systems approach.

Responsible personnel needs knowledge and skills to design an agile operations system.

Competence development

The term 'competence' is used in various settings. This research applies the definition of 'competence' as the ability to apply knowledge and skills to cope with new situations (EMPL 2018c). The process of knowledge creation is termed 'learning'. The consulted literature highlights the importance of experience when it comes to efficient learning processes in order to develop competences. This includes the active involvement of participants and a feedback loop addressing the sense-making and reflection of performed actions. A suitable learning environment supports the learning process by linking information with context. Such a learning environment contains besides the physical place itself amongst others opportunities to reflect, authentic problem situations (context) and motivational aspects. In addition, specific teaching methods foster active involvement of participants and therefore increase motivation and learning outcomes.

Effective competence development requires a combination of teaching methods, learning environment, and subject content.

Learning factories

Learning factories are learning environments aiming to support learning processes through the implementation of authentic problem situations, a close-to-reality abstraction of real value chains and a didactical concept. Especially the didactic concept describes the combination of teaching method, learning environment and subject content. Learning factory training courses consider an alternation of thinking, doing and reflection of participants own actions. Learning factories best support competence development by adding context to the learning subject and by encouraging participant motivation. Subject-specific content at learning factories currently mainly comprises approaches to production optimization. Literature points out limitations of learning factories when it comes to the mapping ability due to limited training time available, limited resources to address issues on several factory levels (e.g. production network, shopfloor), up stream and down stream activities (e.g. purchasing, service) and limited effectiveness caused by focusing on the physical learning infrastructure rather than on developing effective didactic concepts.

The development of a learning factory based training course requires the combination of learning factory potentials as learning environment with a corresponding teaching concept.

Agile operations and competence development

Training to develop competences of responsible personnel is the basis for several operations improvement programs (e.g. lean, six sigma). Similar, to enhance decision-makers competences is one main aspect to develop agile operations. A prerequisite to develop such competences for designing agile operation systems is a holistic teaching concept as agile operations is multi-dimensional and individual to each company. This includes a broad scope of topics from understanding the potential impact and the detection of external change drivers to align and implement countermeasures across organizations functions as well as leveraging the value chain. To the best knowledge of the author of this thesis there is no research addressing the issue of competence development regarding the design of an agile operations system. However, consulted literature states that dynamic and experienced based trainings are promising to develop competences concerning agility. Such trainings need to create opportunities to apply the full scope of the concept of agility, to reflect on those actions and to apply the gained experiences again. Further, consulted literature of related subjects to agile operations highlights the necessity of an authentic learning environment enabling the possibility to manipulate training variables (e.g. dynamism or the impact of training scenarios).

Experiential learning and authentic problem situations are promising to best support competence development regarding agile operations.

Learning factories and agile operations

Learning factories are successfully implemented in practice to develop competences in operations improvement programs (e.g. lean, digital transformation). From the author's point of view the main advantages of learning factories as learning environments for agile operations trainings can be: (1)

application of experiential learning principles; (2) creation of authentic problem situations; (3) enhancing motivation and engagement of participants; and (4) adding dynamism to trainings due to the possibility of influencing scenario parameters. However, the challenge is presumably to depict the entire scope of the topic of agile operations authentically. The review of related studies showed that aspects to include context (e.g. fictional corporate case studies) into shopfloor-based learning factories courses are applicable. Nevertheless, the author of the present research stuy at hand still identifies challenges in the field of the limited mapping ability of learning factories concerning resources (agile operations contains measures across the value chain), time (external change depends on time) and solutions (implementable solutions developed by paticipants themselves).

Based on consulted literature, it can be stated that learning factories are promising learning environments to develop competences related to the subject matter of agile operations.

Table 23 lists the previous derive key-takeaways from the reviewed literature fields.

Table 23: Key-takeaways from reviewed literature

Agile operations (section 2.2)	**Competence development (section 2.3)**
- Agility requires a system approach - Agility counteracts internal and external changes - To adapt quickly on change requires actions on the shopfloor level up to the corporate strategy level as well as adaptions and cooperation across the value network - Implementation of agility is complex and requires know-how and the understanding of external and internal relations - Agility depends on the organization's context and therefore a holistic view is needed - Understanding the business environment and the potential impact of uncertainties on operations is key to the pro-active approach of agility - Monitoring generates the necessary signals to quickly react on change - Aligned with the strategy, pre-defined agility levers are central to quickly respond to external developments - An integrated governance structure to coordinate agility activities is necessary - Management knowledge and competences are crucial for achieving agility	- The concept of competence enables outcome driven development of learning programs - Competence assessment is necessary to ensure learning and to further develop learning programs - Scientific fields of didactics and instructional design support the design of learning programs - Learning is strongly related to experience - Experiential learning with its strong focus on participants involvement promotes experience and thus the learning process - The learning environment links information with context and enables authentic (learning) experiences - The application of experiential learning methods has the potential to enhance participants motivation, engagement and understanding
Learning factories (section 2.4)	**Review of related studies (Section 2.5)**
- Learning factories are constructivist learning environments supporting competence building regarding context-independent and domain specific competences and enhance participants learning - Learning factories aim in general to develop competences for all factory levels - Besides close-to-reality technical infrastructure to enable authentic experiences there is the clear need of a didactical concept - For designing a learning factory course potentials to enhance participants learning need to be addressed - A structured approach for developing a training course is needed - Training courses for industry have just a short timeframe and therefore require rapid knowledge transfer of the course content through well-designed, pre-structured learning processes	- Learning factories support efficient competence development for various operations management topics - As the development of learning factory concepts is complex a guiding framework supports this process - A multi-step process to evaluate the interaction of theory and learning environment as well as the assessment of learning outcomes is required - The possibility to enhance the physical learning environment through case studies and simulations

CHAPTER 3
Aims and objectives

This chapter first introduces the research purpose and formulates the research leading questions. Second, it outlines the intended contribution to literature and practice. Finally, it introduces and discusses delimitations of this research.

3.1 Research purpose and research questions

A research purpose is used to describe the intended achievement of a research study and how this achievement is reached (Karlsson 2016, p. 65). As outlined in chapter 1.2, the following statement defines the research purpose of the present thesis.

"Enabling competence development to design an agile operations system to cope with uncertainty in operations through the development of a training course using experiential learning principles and a learning factory setting."

Derived from this statement the following main leading research question (RQ) aims to develop a training course for agile operations within a learning factory setting.

RQ1: What characterizes a learning factory based training concept that supports competence development regarding the design of an agile operations system?

This main research question contains the need to define the content of the intended training. Therefore, a sub-question is formulated and reads as follows:

RQ1.1: What are the learning objectives for the design of an agile operations system?

Further, consulted literature points out that learning objectives, teaching methods and the learning environment must be synchronized with each other in the development of a didactic concept. Subsequently, following sub-question addresses this issue.

RQ1.2: What are the specific requirements of agile operations learning objectives on teaching methods and the learning environment?

A second research question discusses the fit of the learning factory principle and its deployment to the topic of agile operations. This second leading research question strives to ascertain that learning factories as learning environments and applied teaching methods at the developed training course are suitable for the topic of agile operations.

RQ2: How does the concept 'learning factory' support competence development regarding the design of an agile operations system?

3.2 Intended contribution

The present research study aims to contribute to the scientific subjects and current practice of agile operations and learning factories.

Literature sees training and competence development as an enabler for operations improvement programs (e.g. lean, six sigma). Therefore, answering *RQ 1* and developing a training concept to support competence development regarding the design of an agile operations system contributes to agile operations literature. Further, as the consulted literature points out, the topic of agile operations is recognized by academia and industry. Yet, the majority of consulted literature describes more on what an agility concept should contain whereas only a few authors address how to develop an agility system (see e.g. Sherehiy et al. 2007, p. 448). However, it is not the objective of this research to develop and validate a new approach or a guiding framework to design an agile operations system. The intended contribution is rather to expand existing literature by detailing the proposed 'corporate agility system' (see section 2.2.6). This is to be achieved by answering *RQ 1.1* and breaking down the core elements of the agility concept into competences and, further on, into learning objectives by consulting additional related literature.

Research already proofed that learning factories are suitable learning environments to develop operations improvement competences like lean, digitalization or product development (see section 2.4.4). However, the topic of agile operations with its broad scope requires new approaches when applying the learning factory principle. Literature points out current limitations of learning factories (see section 2.4.5) whereas especially the mapping ability due to limited training time and limited resources (factory levels, up- and downstream activities) seem to apply.

Answering *RQ 1* contributes to the research field of learning factories by addressing some of the identified current challenges in literature. Whereas the answer to *RQ 1.2* provides the required basis for the development of a training course by the determination of specific requirements of agile operations on learning environments and teaching methods. *RQ 2* discusses the suitability of the application of an agile operations training within a learning factory setting. The evaluation results of the developed training with applied methods, extensions to an existing learning factory approach to create an authentic learning environment for agile operations and training organization in general intend to contribute to the research field of learning factories. This contributes as well to the integration of related topics like operations strategy, up- and downstream activities (e.g. purchasing), risk management, changeability or resilience to learning factories.

Literature points out that coping with uncertainty in operations is more important than ever (see chapter 1.1). Therefore, the present research study further intends to contribute to industrial practice. From the author's point of view, competences to design an agile operations system are valuable in order to support companies to gain competitive advantages by applying agile operations. Therefore, competence development contributes to industrial practice by educating future decision-makers as well as by targeted trainings for current industrial employees and managers on all hierarchical levels.

3.3 Delimitation of research focus

This section defines the scope of this research based on the research purpose in combination with requirements and derived delimitations of consulted literature throughout chapter 2 'fundamentals'.

The present thesis focuses on competence development concerning the design of an agile operations system. Following consulted literature, the topic of agile operations is one concept to cope with uncertainties in operations. Other concepts within this scope such as e.g. resilience are not further discussed. The underlying corporate agility system (see section 2.2.5) defines the scope of agility in operations for this research. However, the focus is firmly on agility in operations whereas corporate agility comprises supplementary topics like corporate strategy, corporate culture, finance or marketing. These topics are not considered throughout this thesis except when operations' agility requires a respective linkage.

Consulted literature (see e.g. *Aspin and Chapman 2013; Zlatkin-Troitschanskaia et al. 2015; European Commission et al. 2011*) call for competence driven training and education. The present work considers the concept of competences for the design of an agile operations system training as basis. Further, the focus to develop the intended training is on experiential learning and related teaching methods (see section 2.3.3). Experiential learning is, according to literature, suitable to develop competences for complex topics like operations management (e.g. *Holman 2016; Fish 2007*). This thesis does not intend to contribute to parental learning theories or the scientific fields of learning styles, instructional design and didactics. However, the intended training development takes into account findings from these research fields.

Furthermore, this research is limited to learning factories as physical learning environments. Consulted literature points out that experience is connected to the physical environment and the context of the learning situation. Thus, constructivist learning environments meet the demands of the world of work (see section 2.3.3). Therefore, this research work is limited on developing a training course particularly applicable within a learning factory based setting considering its specific prerequisites. This research follows the guiding framework for the development of a learning factory (and respective teaching modules and learning situations) proposed by *Tisch 2018* as described in section 2.5.3. Further, the focus of this thesis is not the development of a new learning factory but the extension of existing learning factory concepts for the subject matter of agile operations.

The topic of agile operations is not limited to a certain industry and applicable in various settings (Prange and Heracleous 2018, p. 4). However, this research focus on agile operations as concept to cope with uncertainties in manufacturing industry as existing learning factory concepts rely in a majority on manufacturing processes.

Table 24 summarizes the delimitations of this research derived from reviewed literature.

Table 24: Delimitation concerning reviewed literature fields

Agile operations (section 2.2)	**Competence development (section 2.3)**
INCLUDES: - The ‘corporate agility system’ proposed by *Luczak 2017* - Competences related to agility in operations - Methods and tools of the core elements of the corporate agility system: ‘agility drivers’, ‘monitoring’, ‘strategic alignment’, ‘agile operations levers’, ‘governance’ EXCLUDES: - Development of ‘agile organization’ - Corporate culture and behavior - Corporate strategic work - Corporate finance - Marketing	INCLUDES: - Concept of competence as basis for training course development - Experiential learning and consideration of its implication on learning environments - Consideration of different experiential learning methods to enhance participants learning process EXCLUDES: - Development or contribution to the research fields of ‘learning theory’ and ‘learning styles’
Learning factories (section 2.4)	**Review of related studies (Section 2.5)**
INCLUDES: - Extension of existing learning factory for the topic of agile operations which is not addressed in current practice - The requirement of an existing procedure model to develop a competence based learning factory course for agile operations - Contribution to learning factory literature concerning the mapping ability for strategic aspects and incorporation of upstream and downstream activities as potentially necessary to cover the topic of agile operations EXCLUDES: - Development of a structured guiding framework to design learning factories or teaching modules - Development of a new learning factory (environment, products, processes, etc.)	INCLUDES: - Guiding framework proposed by *Tisch 2018* - Consideration of introduced approaches to increase authenticity EXCLUDES: - Stand-alone simulation environment - Long-term project as teaching method

CHAPTER 4
Methodology

This chapter first introduces general methodological considerations concerning the research approach of this thesis and applied data collection methods. Second, the chosen research approach of 'action research' is described in detail. Third, the research framework illustrates the core elements of this research study. Finally, the approach for data collection, analysis and synthesis is described.

4.1 General methodological considerations

Considerations concerning the research approach

In general, a research approach describes plans and actions in order to study a specific field of interest (Creswell 2014, p. 3). Choosing a research approach needs further considerations as existing approaches have individual strengths and weaknesses (Ahlström 2016, p. 68). Literature points out that the internal consistency of a research work is ensured by a methodological fit between (1) research questions – focus of the research study; (2) existing knowledge – maturity of research field; (3) the intended contribution; and (4) the actual research approach (Edmondson and Mcmanus 2007, p. 1156; Ahlström 2016, pp. 70-71).

The development of a new training approach within a learning factory based setting (*RQ 1*) is mainly based on a deductive reasoning approach. Deductive reasoning (top-down approach) tries to reach a conclusion by applying formal guidelines (Meredith 1998, p. 302). Whereas *RQ 2* aims to identify characteristics of learning factories and applied methods supporting competence development of the design of an agile operations system. Hence, the second objective of this research is grounded in an inductive approach to reach a conclusion. Inductive approaches ('bottom-up approach') aim to create knowledge by seeking strong evidence for a conclusion (Karlsson 2016, p. 20).

Table 25 summarizes further considerations concerning the elements for choosing a research approach for the empirical study.

Table 25: Methodological considerations for choosing a research approach

Element	Considerations
Research questions	- Application-oriented research - Development of new connections among phenomena in a specific situation - Deductive (mainly) reasoning for *RQ 1* and inductive reasoning for *RQ 2*
Existing knowledge (chapter 2)	- Profound literature about the scope of the concept of agile operations, competence development and learning factories - Missing specific competences to design an agile operations system - Specific guiding frameworks (mostly limited to certain domains) for the development of trainings within learning factories - Limitations of learning factories require new approaches - Few relevant related studies
Intended contribution	- Development of a new approach (*RQ 1*) - Explorative findings from the developed approach in a certain environment (*RQ 2*)

Based on the considerations presented, an action research approach was chosen for this research study (Table 25).

Characteristics of the applied research approach are introduced in more detail in section 4.2.

Considerations concerning data collection, analysis and synthesis

There is a general distinction between quantitative (e.g. quantifying cause-effect relationships) and qualitative (e.g. exploring new research fields) research (Creswell 2014, p. 4). However, based on the research problem, a combination of quantitative and qualitative methods ('mixed methods' approach) can be applied (Döring and Bortz 2016, p. 27). Such an approach is especially of interest for the investigations of complex and realistic situations (Näslund 2002, p. 321).

The literature consulted showed that the evaluation of training programs pursues two goals: it serves as a basis for assessing of intended learning objectives/competences and for the targeted further development of the training itself (Cachay et al. 2012, p. 1147; Glass and Metternich 2020, p. 38). Hence, the data collection related to the conducted training courses is the main source for answering the research questions. Data to answer *RQ 1* focus especially on the evaluation of competence development. Data as basis for discussing *RQ 2* needs to cover the 'fit' of applied learning factory elements with specific content of agile operations theory. This section provides general considerations about training evaluation.

Throughout this section, a broader view is taken on training evaluation. These considerations serve as the basis for the selection of data collection, analysis and synthesis.

Gosenpud 1990 reviewed types of evaluation studies in experiential learning. According to this work, three major types of evaluation studies are conducted to improve experiential learning:

- Straight evaluation studies:
  These types of studies intend to find out whether the experiential learning method is superior to other existing methods or if the experiential learning methods achieves targeted (learning) objectives (Gosenpud 1990, p. 302).
- Contingency studies:
  The design of these type of evaluation studies is based on the assumption that there is no best way to teach a particular topic because each participant reacts different to teaching elements (Gosenpud 1990, p. 303)
- Assessment of experiential features:
  In difference to other evaluation studies instead of the program itself specific experiential features are in the focus (Gosenpud 1990, p. 303). Examples are exercise duration, scope of decision to be taken in an exercise or the degree of realism (Burns et al. 1990, pp. 268–269).

This research study relates to 'contingency studies' and 'assessment of experiential features'.

Training evaluation in general is a source of frustrations due to various requirements and available approaches (Ewell 2001, p. 4). A classic framework is the often cited and still valuable 'four level model of training criteria' (Arthur et al. 2003, p. 235; Praslova 2010, p. 219). The original model was developed to assess training effectiveness in corporate settings (Praslova 2010, p. 216). The four levels are (1) reaction – how participants react; (2) learning – improvement of knowledge/skills; (3) behavior – participants' change in behavior; and (4) results – results that are made possible due to the attended training (Kirkpatrick and Kirkpatrick 2006, pp. 21–25). Further, *Kirkpatrick and Kirkpatrick 2006* state, that the two indicators of 'behavior' and 'results' are referred to as 'external' and require a longer term perspective. Especially linking the corporate result (e.g. higher quality rate, increase of sales) directly to previously conducted trainings requires a high effort. (Kirkpatrick and Kirkpatrick 2006, p. 63)

Despite the importance of the external indicators, this research considers solely the levels of 'reaction' and 'learning' due to constraints in time and accessibility.

Gosenpud 1990 point out that pedagogical evaluation often lack of sufficient research design, statistical significance and ethical concerns. Further, the authors point out three types of validity, which need to be addressed evaluating experiential learning: (1) internal validity - impact of experiential exercises on participants; (2) external validity - are results of the experiential learning study generalized to other experiential learning exercises; and (3) transfer internalization validity - whether or not the experiential exercises support participants to cope with the real world. (Gosenpud 1990, p. 303)

To ensure the quality of this research the three types of validity must be addressed.

Section 4.4.2 describes the approach to data collection, analysis and synthesis of the present research study in detail.

4.2 Action research

Action research is described as a cyclical process of *"[...] planning, action, and fact-finding about the result of the action." (Lewin 1946, p. 38)* Whereas in traditional research, findings and theories serve as starting point for possible future actions, action based research emphasizes 'research' and 'actions' in parallel (Rowley 2003, p. 132). Key aspects of action research, amongst others, are (1) researchers take action; (2) solving a problem; (3) contribute to knowledge; and (4) action research supports all data gathering methods and types (Gummesson 2000, p. 125).

As stated above, the simplest form of action research contains the three steps proposed by *Lewin 1946* and these are included in any other action research presentation (Coughlan and Coghlan 2016, p. 246). *Coughlan and Coghlan 2016* propose an action research model for operations management with four phases and a pre-step (see Figure 34).

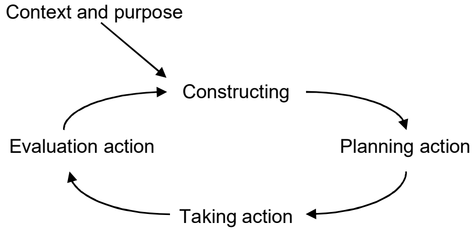

Figure 34: Model of action research (Coghlan and Brannick 2014, p. 9)

Coughlan and Coghlan 2016 describe the steps of action research as follows:

- **Context and purpose**: The research study begins with the necessity of understanding the context and therefore forms the very basis of an action research study.
- **Constructing**: The second step contains the identification of issues (provisionally) and involves the articulation of the theoretical fundamentals. However, the construction might change in the further course of the research.
- **Planning action**: This step needs to be carried out twofold. First, based on the context and construction, the core action must be planned. Second, the research study itself needs a planning step.
- **Taking action**: Execution of the planned action. Data is gained throughout the taken actions. This enables the researcher to interact with elements of the investigated system.
- **Evaluation action**: When pure action is not carefully evaluated the researcher cannot differentiate between success or failure. This step provides the opportunity to learn through reflecting on intended and unintended outcomes. Further, the outcome of the evaluation step is the basis for answering the research questions and leads to the next cycle of action research. (Coughlan and Coghlan 2016, pp. 246-251)

Whereas the introduced model of action research was carried out specifically for operations management related research, action research is present as well in management and educational research (Eden and Huxham 1996, p. 77). Thereby action research is further seen as *"[...] systematic form of enquiry undertaken by practitioners into their attempts to improve the quality of their own practice."* (Whitehead 1994, p. 138) In either way, the application of action research requires preconditions: a real issue (significance, uncertain outcome, implementation of action and research significance); and access (researcher has to gain access to the operation) (Coughlan and Coghlan 2016, p. 240). Table 26 depicts characteristics of action research and considerations in respect to this thesis.

Table 26: Methodological considerations concerning action research (based on Coughlan and Coghlan 2002, p. 224)

Characteristics	Action research	Considerations in respect to this research
Aim of research	- Knowledge in action - Theory building and testing in action	- Development of a new approach (application of 2 action research cycles – see Figure 34) - Contribution to agile operations theory and practice - Contribution to scientific field of learning factories
Type of knowledge acquired	- Particular - Situational - Praxis	- Context specific knowledge (agile operations → competence development → learning factories) - Includes gained knowledge from taken actions - Test of teaching methods and principles for specific situations (agile operations, learning factories)
Nature of data	- Contextually embedded	- Data source are taken actions in the subject area of interest - Type and source of data: observations, knowledge tests, peer review, participant questioning (For more information see section 4.4.2)
Validation	- Experiential	- Developed training course is tested in real learning environment (following the cyclical action research approach)
Researcher's roles	- Actor - Agent of change	- Constructing the initial training course - Further development (cyclical approach) of the training course - Trainer - Observer

As stated in Table 26, action research generates primarily situation specific knowledge. However, literature points out that action research further generates emergent theory (developed from the synthesis of the application of theory and thereby gained data from taken actions) and contributes incrementally (from particular knowledge to universal knowledge in small steps) to theory building (Eden and Huxham 1996, p. 80).

Further, literature points out that maintaining quality in action research requires further consideration due to its practical focus and different possible alternative actions (Coughlan and Coghlan 2016, p. 256). In this context *Pasmore et al. 2008* state, that to ensure quality action based research needs to be (1) rigorous - e.g. data driven, multiple methods, co-evaluation; (2) reflective - e.g. referential, community of practice, repeated application; and (3) relevant - e.g. practical, re-applicable, teachable (Pasmore et al. 2008, p. 568). In addition, literature highlights the necessity of a clear and structured research report (e.g. Coughlan and Coghlan 2002; Rowley 2003; Coughlan and Coghlan 2016).

As previously stated, from the author's point of view, the methodological fit between research question, existing knowledge, intended research contribution and action based research as guiding research approach exists. The following Table 27 shows the proposed content of an action research report (Coughlan and Coghlan 2016, p. 256), in relation to the structure of the present thesis and remarks on the three quality factors proposed by *Pasmore et al. 2008*.

Table 27: Content of an action research report and remarks to ensure research quality (based on Coghlan and Shani 2014, pp. 529–530)

Action report key content	Chapter	Remarks to ensure research quality
Purpose and rationale for action and inquiry - Reasoning why action research is desirable - Intended contribution	2 Fundamentals 3 Aims and objectives 4 Methodology	RIGOR - Research gap identified and addressed - Clear reasoning for action research approach (e.g. methodological fit) REFLECTIVE - Clear linked to existing literature and relevant research RELEVANT - Relevance for action research outlined
Context - Understanding the organizational (business) and academic context	2 Fundamentals 4 Methodology 5 Conception	RIGOR - Contextual data (academic and practice) is reviewed REFLECTIVE - Clear linked to past research and existing literature - Related studies and learnings considered - Builds upon previous experiences of the researcher (trainer, learning factory operator, consultant for relevant industry projects) RELEVANT - Structured literature study
Methodology and method of inquiry - Role of action researcher - Ethical issues	4 Methodology 5 Conception 6 Results	RIGOR - Process description of selecting applied methods for the inquiry - Planning of implemented actions REFLECTIVE - Extensive description of action and research cycle - Gained learnings are formulated and applied throughout the empirical work RELEVANT - Applied methods of inquiry enable the further development of the empirical work (proven in the field of interest) - Gained data is the basis to answer the research questions
Design - Data collection and generation - Cycles of action research - Building relationship	4 Methodology 6 Results	RIGOR - Consideration of 'research quality' throughout the study - Data gathering, analysis and synthesis ('mixed methods' approach introduced and discussed in detail REFLECTIVE - Level of implementation introduced and discussed RELEVANT - Methodological fit discussed
Narratives and outcome - Describe the story and outcomes (intended and unintended)	6 Results 7 Conclusion 8 Summary and Outlook	RIGOR - Process and outcome of research cycles are described REFLECTIVE - Researchers' involvement is described and discussed RELEVANT - Data gathering methods ensure the capturing of 'real' situations - Research contribution is formulated
Reflection on the story and outcomes - Analyze story and reflection - Make judgement on process and outcomes	7 Conclusion	RIGOR - Discussion of research process application REFLECTIVE - Peer discussions throughout research process (application of process and research outcome) RELEVANT - Research contribution is discussed
Discussion - Link story to theory - Discuss story and outcomes - Discuss action research process	7 Conclusion	RIGOR / REFLECTIVE / RELEVANT - Discussion of research process outcomes - Discussion of research contributions (actionable knowledge, scientific contribution)

4.3 Research framework

A conceptual research framework describes the central elements of the field of interest and their expected connections either graphically or in a written form (Miles and Huberman 2008, p. 20). It can be seen as model of 'what' the research study investigates (Karlsson 2016, p. 17). Further, the research framework is the basis for a structured data collection and the subsequent analysis (Karlsson 2016, p. 17).

The elaborated research framework for the present study is based on the intended research contribution and existing knowledge (see chapter 2). Further, the elaborated framework incorporates gained information from literature about research methodology (see chapter 4). Figure 35 shows the graphical illustration of the underlying research framework.

The critical training course element is located at the center of the framework. This is illustrated as a cycle of planning, taking action, evaluation and further development (*RQ 1* and *RQ 2*) as required by the chosen research approach.

The first foundation of this research is agile operations theory. The expected connection between agile operations theory and intended training course development involves the intermediate step of the formulation of agile operations competences. These specify 'what' to teach (*RQ 1.1*). Further, these competences frame the requirements for the to-be developed learning environment as an inherent part of the central training course element (*RQ 1.2*).

The second foundation is grounded in existing knowledge in relation to competence development and the concept of competence. Whereas learning is seen as basis to knowledge creation (see section 2.3.2), learning factories are seen as strong enabler for operations management related competence development. Consulted literature provides general considerations about competence development and learning (e.g. learning styles, instructional design, didactics) as well as the specific knowledge about e.g. teaching methods or strength and limitations of learning factories. Thus, consulted literature of this second foundation provides the frame for possible solutions of 'how' to teach (*RQ 1*). In addition, a connection between the concept of competence and agile operations theory is expected to support competence formulation (RQ 1.1).

Methodological considerations provide especially the procedural input of how to conduct the research study.

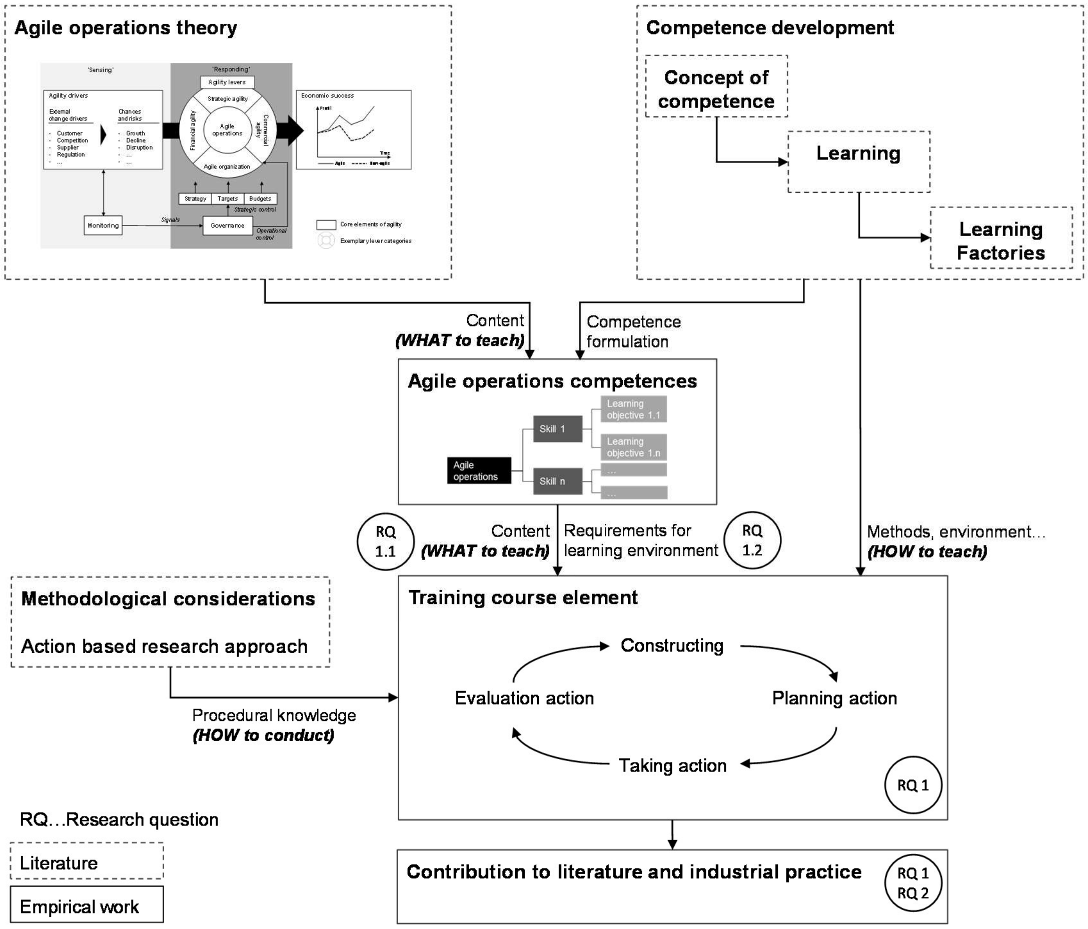

Figure 35: Conceptual research framework (own illustration)

The study conducted throughout the central training course element results in the expected research contribution. As previously described, the action research approach requires a transparent procedure for data collection, analysis and synthesis in order to ensure 'rigor'. Therefore, the next section introduces the chosen approach to data collection, analysis and synthesis.

4.4 Conducted research steps and empirical data

This section is further segmented into describing the sequence of conducted research steps and the chosen approaches for data collection, analysis and synthesis.

4.4.1 Conducted research steps

This section aims to outline the conducted steps throughout the empirical research study. First, the overall sequence of conducted steps is introduced. Second, the application of the chosen research approach is outlined.

Sequence of conducted steps (overview)

Step 1 (chapter 2): The literature study considers two main literature fields (agile operations and competence development) and provides the necessary basis for the intended contributions. This step concludes with the authors view on the existing knowledge.

Step 2 (chapter 5): Consulted literature highlights the formulation of competences and its consisting elements (see section 2.3.1). Therefore, the starting point for the intended training development is the formulation of relevant competences. Through a structured review of available literature about agile operations competences (and related domains), the main competence of designing an agile operations system was formulated and broken down into its consisting elements.

Step 3 & 4 (chapters 5 and 6): The central element to this research is the training course development. As previously defined, the development of the training course is based on the guiding framework proposed by *Tisch 2018*. Data gathering methods for the training evaluation are introduced in following section 4.4.2.

Step 5 (chapters 7 and 8): Finally, the results are outlined and discussed. This includes the reflection on the applied research approach and its implications, the discussion of intended and unintended contributions to literature and practice as well as a brief outlook on future research.

Figure 36 shows the principal sequence of conducted steps throughout this research study.

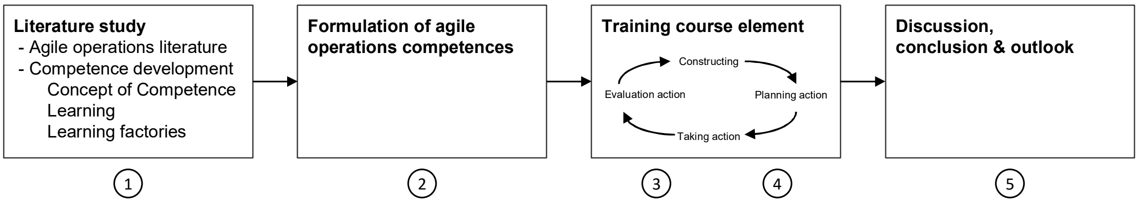

Figure 36: Sequence of conducted steps (own illustration)

Application of the action research approach for training development

As described above (see Figure 36 - 'step 3 & 4'), the action research approach was applied foremost within the central training course element. Figure 37 shows the cyclical process of the applied action research approach.

Action research cycle 1

The overall objective of action research cycle 1 was to 'experiment and learn'. As *pre-step* (defining context and purpose) served learnings from the conducted literature study (see chapter 2) as well as three years of personal experience from the author of this thesis. Personal experience of the author contains teaching learning factory courses for students and for industry representatives (lean, digitalization, industrial engineering and factory planning), supervising a master thesis about the development of a service learning factory (see *Sadaj et al. 2020*), being responsible for the further development of Graz University of Technolgoy's LEAD Factory[9] and project expertise gained from industry cooperation (topics were e.g. operations improvement, digitalization, factory and network planning). The phase of *constructing* (identifying issues and articulation on fundamentals) resulted in the formulation of competences and subsequently on the derivation of requirements for the intended training course. Within the phase of *planning action,* the training course itself was elaborated. This included, amongst others, developing the learning environment, teaching methods, media and evaluation methods. The training course conception is described in detail in chapter 5. The execution ('*taking action*') of the developed course was done due to constraints in time and availability in two steps. First, teaching modules concerning 'sensing' (understand external change drivers and monitoring – section 2.2.6) where taught. Second, the topics of 'responding' (strategic alignment, agile operations levers and governance – see section 2.2.6) were taught with a different group of students. The *evaluation action* was the basis for the further development of the course element and the enhancement to action research cycle 2. Results of the evaluation action are presented and discussed in chapter 6.

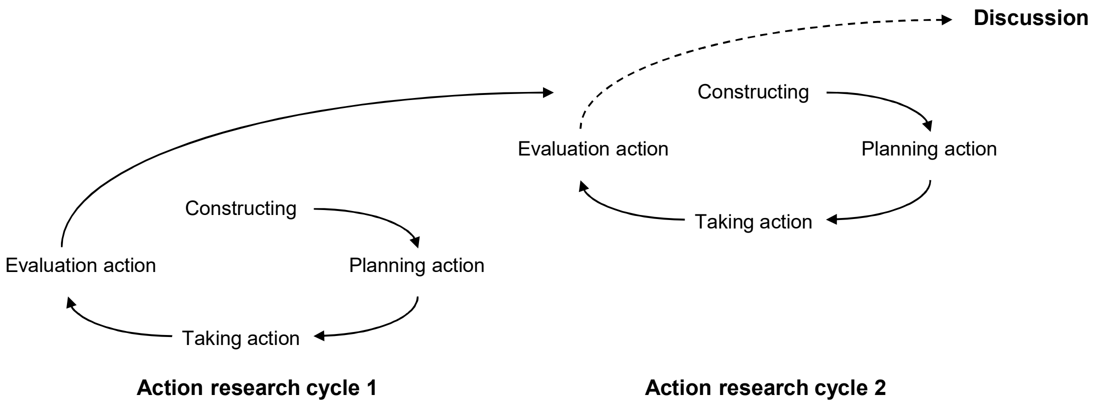

Figure 37: Action research cycles (own illustration)

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[9] See https://www.tugraz.at/institute/iim/infrastruktur/lead-factory/ (2020-11-02)

Action research cycle 2

The second research cycle aims to further develop and test implemented learnings from research cycle 1. Based on the evaluation action of cycle 1 (see section 4.4.2), *constructing* involved the interpretation of gained data resulting in the identification of improvements. Activities in the following step of *planning action* aimed to elaborate solutions to overcome identified barriers based on consulted literature. This includes changes to the learning environment, teaching methods, media and course organization. The step of *taking action* contained the actual execution of the further developed training course. In research cycle 2, two seperate training courses were held. Both actions took place on consecutive days with two different group of students. The author chose to conduct two training courses in order to increase the number of participants and therefore to increase the in order to increase the relevance of this research study. In addition to the learning factory supported training courses, a supplementary single frontal lecture was held. The frontal lecture served to get a comparison of the different teaching methods for the discussion of the research results. The content of the frontal lecture comprises the same theoretical inputs as the learning factory supported variant. *Evaluation action* was performed for both held training course types. The gained results of this second evaluation phase are considered as the final results of this study and are presented and further discussed throughout chapters 6 and 7.

Figure 38 illustrates the linear sequence of the steps 'taking action' of both research cycles including the intended objectives.

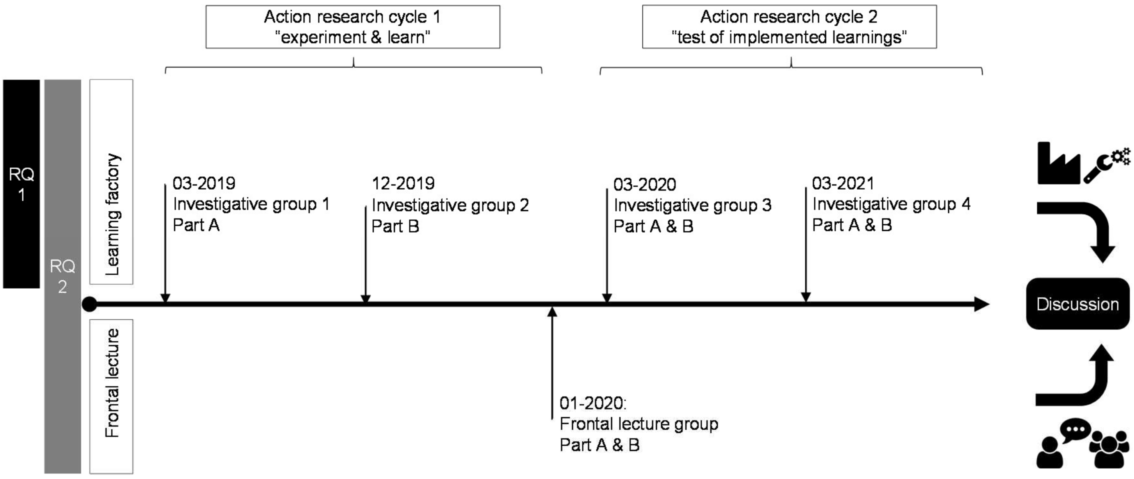

Figure 38: Linear sequence of taken actions (own illustration)

As previously described, the discussion comprises the reflection on the applied action research approach as well as the summary and critical reflection on the intended and unintended research contributions.

4.4.2 Data collection, analysis and synthesis

This section aims to give an overview of applied data collection methods and the approach to data analysis and synthesis to answer the research questions.

As stated in section 4.1, the data gathering approach needs to form the basis for answering the research questions on 'reaction' and 'learning' level (see *Kirkpatrick and Kirkpatrick 2006*) while ensuring validity. The process of choosing the applied methods considers literature introduced in section 2.3.1, methodological consideration concerning the chosen research approach (see chapter 4.2) and learnings from related studies in section 2.5. These learnings can be summarized as follows:

- Section 2.3.1 introduces five principal methods of competence assessment, namely self-report, job requirements, student engagement, achievement tests and role-plays (Braun and Mishra 2016, p. 51).
- In general, the chosen action research approach supports the use of different, both quantitative and qualitative data ('mixed methods' approach)
- The review of related studies showed that solely *Faatz 2017* used different data collection methods (see Table 28).

Table 28: Applied data collection methods in related studies

Author	**Target**	**Applied data gathering method**
Gossmann and Nyhuis 2012	Concept development for a learning factory for changeability	Survey to identify observable competences (no further specification to data gathering method)
Riffelmacher 2013	Validation of the qualification concept for using a learning factory for multi-variant assembly	Post-test based on self-evaluation
Faatz 2017	- Evaluation of the developed learning module and simulation game - Evaluation of the impact of the learning module and simulation game	- Pre- post knowledge test - Peer review - Intermediate course results - Participant surveys
Andersen et al. 2019	- Course development on changeability (learning factory based on a FESTO didactic platform) - Support of learning factory approach to theoretical knowledge transfer	Student feedback (no further specification to data gathering, method)

Taking into account the general considerations concerning data collection, analysis and synthesis and to gather as much data as possible to answer *RQ 1* and *RQ 2*, this research follows a similar approach as *Faatz 2017* and uses a combination of qualitative and quantitative data. This goes along with a proposed training evaluation approach for higher education based upon Kirkpatrick's 'four level model of evaluation' (Praslova 2010, p. 222). First, the level of 'reaction' is evaluated using a questionnaire to gather the experience from a participant's point of view. Further, observations of intermediate results and behavior of participants throughout the training course made by peers and the trainer (author of this thesis) contribute to gather information about participants' reactions. Second, the level of 'learning' is addressed by the determination of participants' knowledge with a pre-post test approach. Likewise, the observation of intermediate results by peers and the trainer contribute to assess participants learning. This approach is considered to enable a broader view on the actions taken. Table 29 shows chosen data collection methods, their characteristics and expected results.

Table 29: Overview of applied data gathering methods

Method	Characteristics	Time of data gathering	Expected results	Considerations concerning validity (contribution)
Pre-post knowledge test	- Written - Standardized	Before and (immediately) after training course	- Existing knowledge - Learnings	- Internal validity (impact of training course) - External validity (how do applied methods work within a learning factory setting)
Peer observation	- Accompanying - Semi-standardized - Qualitative	During training course	- Participants reaction to training setup - Inference of applied teaching methods, learning environment etc.	- External validity (how do applied methods work within a learning factory setting) - Transition validity (how can participants cope with 'real' situation)
Evaluation of intermediate training results (Trainer, peers)	- Accompanying - Qualitative	During training	- Learnings - Application of knowledge in new situations (competence) - Inference of applied teaching methods, learning environment etc.	- Internal validity (impact of training course elements) - External validity (how do applied methods work within a learning factory setting) - Transition validity (how can participants cope with 'real' situation)
Questionnaire	- Written - Standardized	After training course	- Reaction to training setup from participants point of view - Inference of applied teaching methods, learning environment etc.	- Internal validity (impact of training course elements) - External validity (how do applied methods work within a learning factory setting)

The used pre-post knowledge test, peer observation protocol and questionnaire are shown in Appendix B. In the following, the content of each data gathering method is described briefly.

Pre-post knowledge test: A necessary basis for competences are corresponding knowledge elements (Tenberg 2011, pp. 84–85). Therefore, a pre test measurement is followed by the treatment (learning factory course) and a second measurement (post test). A comparison of these two measurements provides information about possible changes that have occurred throughout the treatment (Döring and Bortz 2016, p. 202).

The measurement applied in this study is a written test consisting of six questions. The questions are based on the derived learning objectives and intend to address the understanding of basic theoretical knowledge (Anderson 2001, XII). The questions are rated based on the number of correct answers per question. For none or a not correct answer, zero points are awarded. For each correct answer, one point is given to the participant. As the test is performed twice, the first test before the learning treatment is expected to achieve less points than the second attempt after the training course. This addresses the comparison of the different investigative groups (action research cycle 1 vs. cycle 2) to assess the further developments and the discussion of the teaching method 'frontal lecture' and the learning factory setting. However, as stated above – it is not the target of this research to identify the superior teaching method. This research discusses if applied learning factory elements support the competence development regarding agile operations.

Further, participants are asked to share information about their field of study and progress. This supports the validity of the study as the investigative group (learning factory treatment) is first comparable among the different participant groups. Second, the investigative group and the frontal lecture group should be similar concerning these control variables (as randomization was not possible due to constraint of accessibility) in order to discuss *RQ 2*.

Peer observation: *Döring and Bortz 2016* state that in the context of an empirical research, scientific observations enable obtaining objective findings when a rule-guided procedure is applied. Particularly relevant are data in the form of observation protocols. Further, the authors stress the selection of suitable observers by means of e.g. experience, motivation or reliability. (Döring and Bortz 2016, pp. 324-330)

Therefore, a semi-structured peer observation sheet based on content proposed in literature (Centre for Teaching Support & Innovation 2017; *Brent R. and Felder 2004*) was used to examine following issues:

- Organization of exercises
- Importance of exercises to the course
- Consistency with course objectives
- Appropriate length of exercises (including detailed time observation)
- Exercise difficulty and challenge
- Course information (media, handouts etc.)
- Subjective evaluation of intermediate training result
- Additional information (good / bad aspects; improvements)

Throughout the taken actions, at least one peer (scientific research assistants with experiences in teaching learning factory trainings) observed the training course and provided insights by using the peer observation sheet (see Appendix B). Prior to the training, peers were informed by the author of this research about the course organization and intended objectives.

Evaluation of intermediate training results: Based on the formulated competences and its consisting elements (corresponding knowledge and observable actions) intermediate results were evaluated by the author of this research and discussed with peer observers directly after the training sessions using a semi-structured evaluation sheet. The evaluation is based on the outcomes of exercises like presentations, participants' actions or elaborated improvement concepts. Similar to the previous described peer observation, enables the simultaneous use of multiple observers a comparison of results and subsequently a minimization of observation errors (Döring and Bortz 2016, p. 328).

Questionnaire: *Döring and Bortz 2016* state that the questionnaire method – similar to the interview method – is able to assess aspects of participant experiences. Advantages of questionnaires in relation to interviews are e.g. the efficacy (self-administration by participants) and the increased anonymity. The authors stress the importance of using proven individual items and scales from the literature for the construction of a questionnaire. In this context, the authors highlight the possibility to take single items from extensive scales. Single items are used to measure a characteristic. However, for important or more complex questions several similar or aligned items that measure together a characteristic should be used. (Döring and Bortz 2016, pp. 398-413)

This study used a paper-pencil questionnaire in a face-to-face group situation to get a high response rate (as proposed by Döring and Bortz 2016, p. 413). The questionnaire used consists of two parts. First, groups of items related to aspects of the 'fit' between learning environment and learning content are assessed on a five-point Likert-scale. Further, additional comments are explicitly requested (see Appendix B). Due to the specific research questions to answer, the applied questionnaire is based on elements from two already tested and standardized frameworks of education evaluation. One of these instruments is the 'Teaching-Learning Environment Questionnaire' (see *Herrmann et al. 2016, Entwistle et al. 2003*) and the 'Learning Experience Questionnaire' (see *Borglund et al. 2016*). Second, the questionnaire contains closing open-ended questions as proposed in literature (Centre for Teaching Support & Innovation 2017, p.10). Table 30 outlines the underlying factors of surveyed items.

Table 30: Objectives of inquiry (questionnaire)

Factor	**Item(s)**[10]	**Objective of inquiry**
Constructive alignment	1, 2, 3, 4	Alignment between training course objectives, teaching methods and used media (Entwistle et al. 2003, p. 91)
Stimulating tasks	5	Students perception of the importance of given problems in learning situations (Borglund et al. 2016, p. 10)
Exploration and own experience	6,7	Contribution of participants experiences made within the training course to the overall learning process (Borglund et al. 2016, p. 10)
Challenge	8	Perception of challenge of learning situations – challenging and stimulating but not overwhelming to students (Borglund et al. 2016, p. 10)
Understanding of the subject	9, 10, 11	Deep understanding enforced through e.g. (1) relation of the course to prior knowledge; (2) link of subject matter to practical examples and (3) the support of learning activities to enhance key-concept understanding (Borglund et al. 2016, p. 11).
Adequate prior knowledge	12	Have participants the necessary knowledge base or is this knowledge sufficiently addressed throughout the training course (Borglund et al. 2016, p. 12).
Time for reflection	13	Reflection opportunities of participants on their learnings throughout the course (Borglund et al. 2016, p. 12).
Collaboration	14	Opportunities for participants to collaborate (Borglund et al. 2016, p. 12)
Support	15	Opportunity for participants to get support in their learning from trainer/peer participants (Borglund et al. 2016, p. 12).

The selection of data gathering methods is influenced by constraints (e.g. availability participants, participants' reachability, time constraints, possibility of training execution). Especially statements concerning the 'transition validity' (coping with real world) is limited and must be addressed throughout the critical reflection (see chapter 7). However, from the author's point of view, the gathered data is sufficient to answer the research questions and to ensure validity.

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[10] See full questionnaire in Appendix B

Figure 39 shows the principle scheme of participant groups, interventions, respective course content and data collection methods.

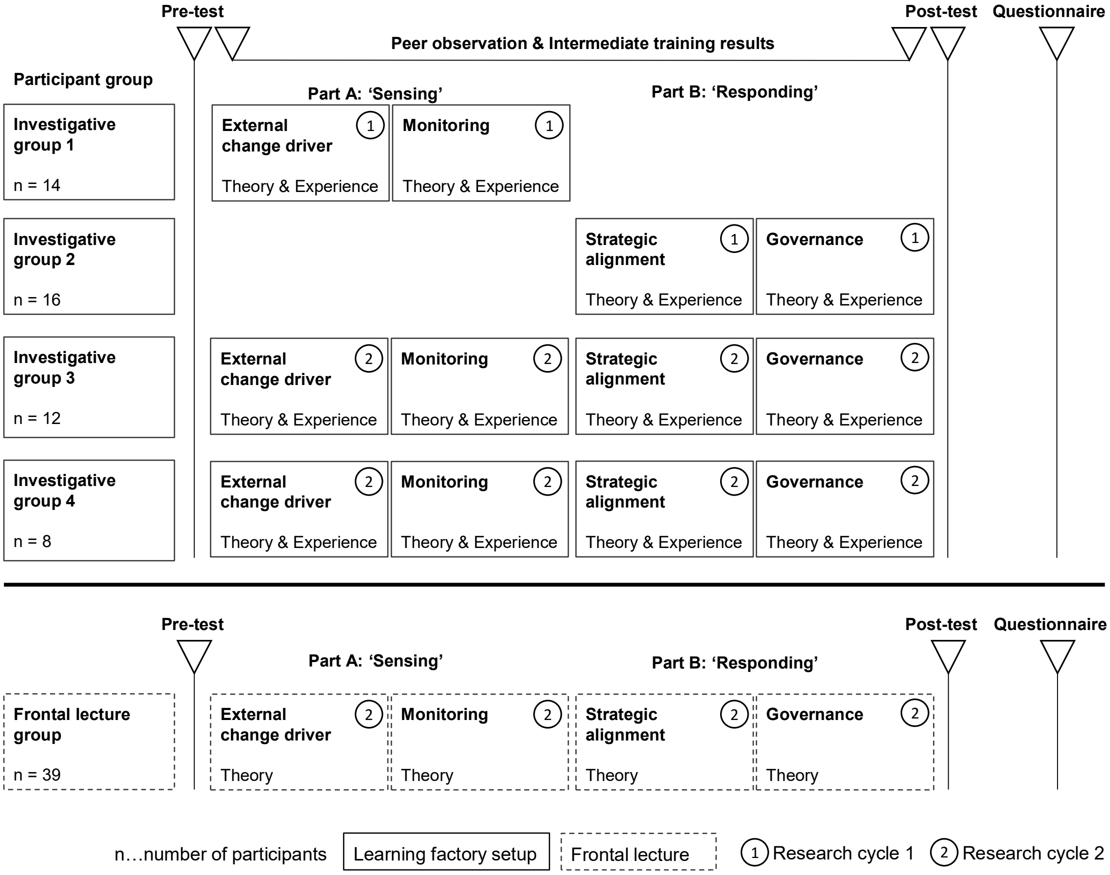

Figure 39: Overview of conducted study – participant groups, interventions, content and data collection method (own illustration)

The evaluation of training course elements is based on the separate analysis of the applied data collection methods and a subsequently conducted data triangulation. In a first step, data obtained from the investigative group 1 is analyzed separately and results are compared to each other in order to identify potential contradictions. Next, data from the different data collection methods are triangulated and interpreted. Subsequently achieved analysis results are the basis for the further development of part A ('sensing') of the developed training course. The same procedure is applied to the intervention of investigative group 2 (part B: 'sensing') in order to complement the results of action research cycle 1. These results define specific course elements, which require targeted further development.

Action research cycle 2, as previously described, aims to: (1) further develop training elements; (2) test new and adapted elements and (3) gain data as basis for the intended contributions. Similar to action research cycle 1, data from investigative group 3 and investigative group 4 are first analyzed separately, compared to each other, then triangulated and finally interpreted.

In addition, to measure the impact of adapted and new elements, each data source was compared and analyzed separately across research cycle 1 and 2. Triangulated results were compared and analyzed similarly.

Figure 40 shows the approach to data analysis.

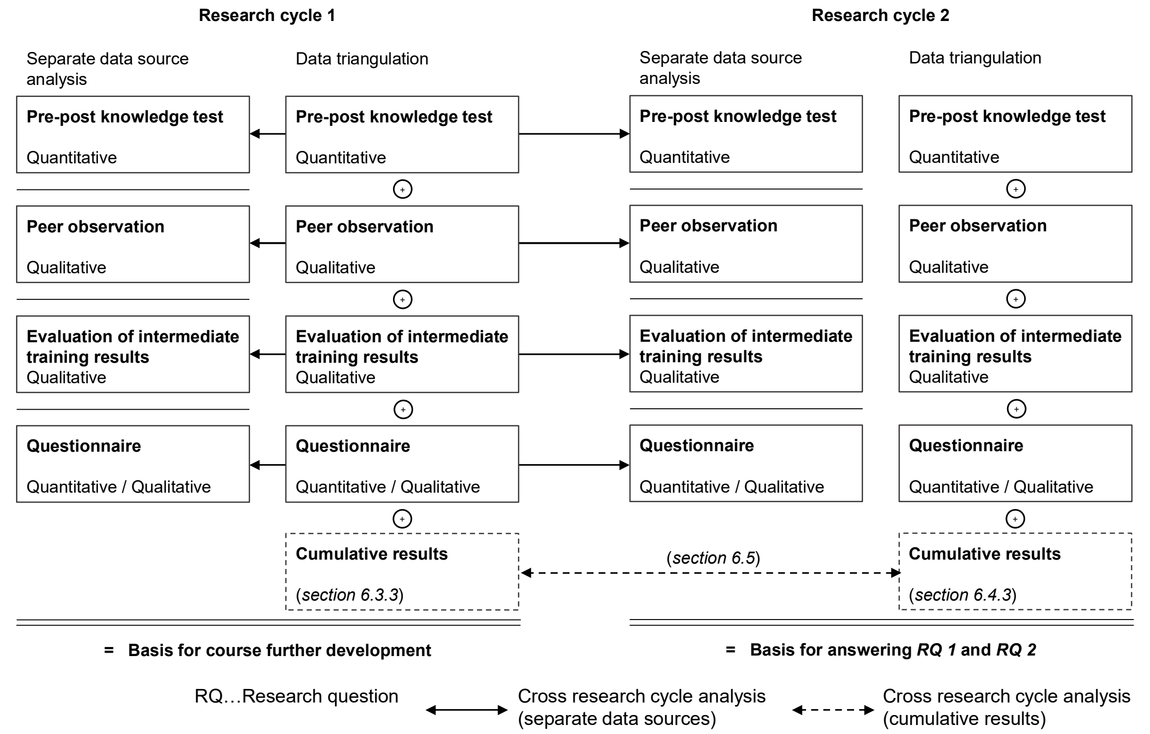

Figure 40: Data analysis approach to answer *RQ 1* and *RQ 2* (own illustration)

These results contribute to answer *RQ 1* confirming in literature existing cause-effect relations concerning the concept of learning factories and the inclusion of a subject matter to learning factory settings ('confirmatory research' - Wagenmakers et al. 2012, p. 633). Further, these results serve to identify elements of the developed teaching approach supporting competence development of agile operations – the 'fit' between learning setup and subject matter (*RQ 2*). Gained findings are expected to contribute to the research field of learning factories as these elements address topics, which interfere with current limitations of learning factories stated in literature (see section 2.4.5).

Finally, findings comparing the frontal lecture group to the investigative groups 3 and 4 (pre-post test and questionnaire results) were included to discuss research questions and research contributions in more detail. As groups were not randomized but the independent variable (teaching method) is differentiated and the effects (dependent variables) were measured, this approach can be described as 'quasi-experimental study' (Döring and Bortz 2016, p. 193). Figure 41 shows the different treatments and measurement methods. *Döring and Bortz* further suggest using a two-group experimental design with a two-step independent variable (learning treatment) and a scaled dependent variable (learning success) (Döring and Bortz 2016, p. 195).

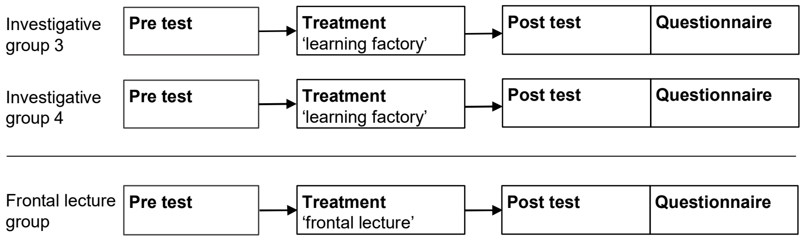

Figure 41: Treatment and dependent variables of quasi-experimental study (own illustration)

CHAPTER 5
Conception

This chapter outlines the developed teaching approach throughout action research cycle 1 and 2 to answer the research questions formulated in chapter 3. First, this chapter describes briefly the underlying guiding framework to develop learning factory training courses by *Tisch 2018* (see section 2.5.2) and outlines conducted development steps of this research. Second, it introduces results of the competence formulation. Third, it describes the derivation of requirements to the learning environment. Fourth, this chapter outlines characteristics of the developed training course, which includes elements like course organization, teaching methods or the sequence of learning situation descriptions. Finally, it introduces developed extensions to the learning environment specifically for the subject matter of agile operations.

Above of that, this chapter presents the final results (action research cycle 2) of the developed training course. Sections wherever further developments were necessary, are highlighted, reasoned and reference is made to the corresponding learnings from the first research cycle. The results from each research cycle are introduced and discussed throughout the following chapter 6.

Preliminary results addressing the conception of the teaching concept were published in the course of this research project.

Karre, Hugo; Hammer, Markus; Ramsauer, Christian (2018): Learn how to cope with volatility in operations at Graz University of Technology's LEAD Factory. In Procedia Manufacturing 23, pp. 15–20. DOI: 10.1016/j.promfg.2018.03.154.

Karre, Hugo; Hammer, Markus; Ramsauer, Christian (2019): Building capabilities for agility in a learning factory setting. In Procedia Manufacturing 31, pp. 60–65. DOI: 10.1016/j.promfg.2019.03.010.

Further, conducted bachelor thesis under the supervision of the author of this thesis contributed partially to the resulting training course (see *Saiko 2019*; *Rinnhofer 2021*).

5.1 Approach to design the agile operations learning factory training course

As described in section 2.5.2, the referred to model from ***Tisch 2018*** consists of three design levels: (1) macro – learning factory level; (2) meso – teaching module level; and (3) micro – learning situation level. Further, the guiding framework proposes for procedural steps relevant methods and tools (Tisch 2018, pp. 107-160). Each of the three design levels answers two central questions ('didactical transformations'): (1) *WHAT* are relevant learning objectives and (2) *HOW* to address those learning objectives within a learning factory setting (Tisch et al. 2016, p. 1360).

However, this research aims to integrate agile operations to an existing learning factory and not to develop a new learning factory (see chapter 3.3). Hence, this research study did not consider all steps of the proposed guiding framework. This section introduces the taken key steps throughout this research on each design level. Further, explanations in this section refer to subsequently described development results of conducted empirical work.

5.1.1 Macro level – learning factory

The guiding framework includes to the macro level in general following steps: 'target definition' (learning factory- and learning targets), 'planning of the learning factory environment' (structure, conception- and detailed planning), 'verification', and 'program creation' (including modularization) (Tisch 2018, pp. 121–136). Figure 42 shows proposed macro level steps of the guiding framework by *Tisch 2018*.

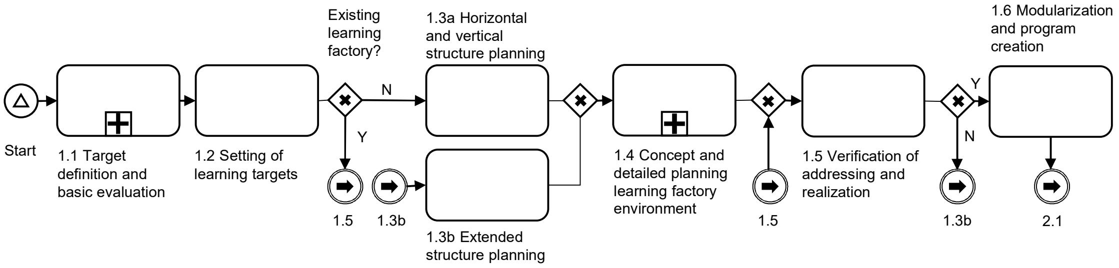

Figure 42: Design of the macro level (learning factory) (based on Tisch 2018, p. 119)[11]

Table 31 summarizes the main targets of each procedural step and adds remarks to this research study.

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[11] As proposed by *Tisch 2018* - BPMN 2.0 is used as process notation standard

Table 31: Conducted steps on the macro level throughout this research
(based on Tisch 2018, pp. 121–136)

Step	**Target**	**Remarks to this research study**
Target definition and basic evaluation (1.1)	- General learning factory target definition - Definition of requirements - Definition of boundary conditions	- The general learning factory target is not addressed throughout this research - The target is solely to add the subject matter of agile operations to an existing learning factory ('learning factory' according to the definition in a narrow sense by *Abele 2018*) - The learning factory morphology (initial situation) of the learning factory employed in this research study can be found in Appendix E and shows exemplarily the boundary conditions to this research study
Setting of learning targets (1.2)	General target setting based on intended competence development objectives	Formulation of intended competences and its consisting elements (skills, learning objectives) are described in chapter 5.2.
Horizontal and vertical structure planning (1.3a) Extended structure planning (1.3b)	- Definition of considered horizontal production life cycle (e.g. product life cycle) - Definition of necessary vertical factory levels (e.g. network level, shopfloor level)	Chapter 5.3 contains: - Derived requirements from learning objectives on the learning environment (product, factory levels etc.) - Introduction and reasoning of chosen horizontal life cycles and vertical factory levels
Concept and detailed planning of the learning factory environment (1.4)	- Identification of learning factory design alternatives for products and defined factory levels - Assessment of design alternatives	- This research builds upon existing learning factories and does not intent to change the given basic characteristics (products, process, infrastructure) - This research considers 'extensions' to existing learning factories (e.g. additional products) in order to add the topic of agile operations to a working learning factory - Chapter 5.5 introduces implemented solution approaches (course elements) to derived requirements (learning objectives) in detail
Verification of addressing and realization (1.5)	- Evaluation of the fit between chosen solution (1.4) and learning targets (1.2) - Realization of concepts	- Developed solution approaches address the intended competences (learning objectives) - Developed solution approaches are implemented, tested, further developed (action research cycle 1) and re-tested in action research cycle 2
Modularization and program creation (1.6)	Modularization of learning objectives to create the overall learning factory program	- Subject matter of agile operations was added to the existing course program of the employed learning factory of this research study - Modularization of the topic itself is based on literature (see chapter 2.2) and the formulated competence and its consisting elements (see chapter 5.2)

5.1.2 Meso level – learning modules

Tisch 2018 states that the meso level includes an analysis of learning module requirements and general conditions, a target group specific description, detailing and operationalization of learning objectives and technical and methodological design of the learning module. The meso level is based on the results of the macro level or serves as starting point to learning module extensions with no impact on macro level elements. (Tisch 2018, pp. 137–155)

Figure 43 shows the meso level steps of the guiding framework by *Tisch*.

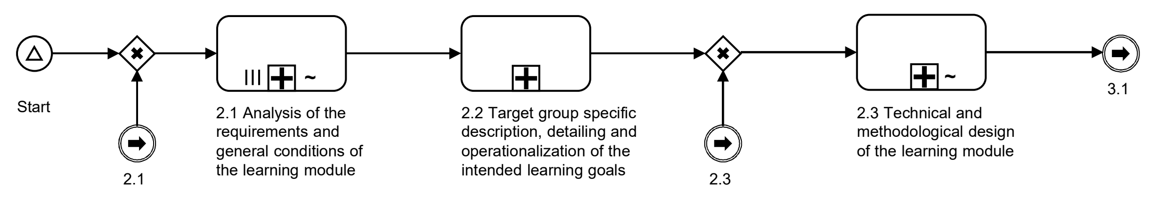

Figure 43: Design of the meso level (learning modules) (based on Tisch 2018, p. 119)[12]

Table 32 describes the activities carried out on the meso level throughout this research study in brief.

Table 32: Conducted steps on the meso level throughout this research (based on Tisch 2018, pp. 137–155)

Step	Target	Remarks to this research study
Analysis of the requirements and general conditions of the learning module (2.1)	- Definition of requirements and boundary conditions of each learning module - Identification and description of addressed roles	- Learning modules are defined based on the formulated competences (see chapter 5.2) - Requirements for each learning module are derived from formulated competences and its consisting elements (see chapter 5.3) - Roles for the design of an agile operations system are outlined in chapter 5.2
Target group specific description, detailing and operationalization of the intended learning goals (2.2)	- Detailing of defined learning objectives at step 1.2 (macro-level) - Operationalization of defined learning objectives	- Detailed learning objectives are formulated based on competences identified in literature (see chapter 5.2) - Learning objectives are operationalized based on consisting elements of competences (knowledge elements and observable actions) and learning module definition (see chapters 5.2 and 5.4)
Technical and methodological design of the learning module (2.3)	- Sequencing of the learning modules (including strategies to plan learning processes) - Detailing, adaption and extension of defined learning environment infrastructure at step 1.4 (macro level)	- Learning process strategies for each learning module are chosen and outlined in chapter 5.4 - Chapter 5.5 introduces key-extensions (learning factory elements) to an existing learning factory to include the subject matter of agile operations

5.1.3 Micro level – learning situations

According to *Tisch 2018,* the micro level represents the most detailed level of planning. Single learning situations are designed taking into account meso level results and general strength of learning factories (see section 2.4.3). *Tisch 2018* derives two rules for designing single learning situations: (1) output orientation - how to reach the learning objective; and (2) practical orientation - emphasize practical activities rather than theory inputs. Hence, *Tisch 2018* proposes first to design experimentation and exploitations activities by identification of activities and knowledge elements of formulated competences, design of a scenario addressing these elements and elaboration of necessary participant information. Then, necessary theoretical input and reflection activities are planned based on practical activities. (Tisch 2018, pp. 155–158)

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[12] As proposed by *Tisch 2018* - BPMN 2.0 is used as process notation standard

Figure 44 depicts procedural steps on the micro level.

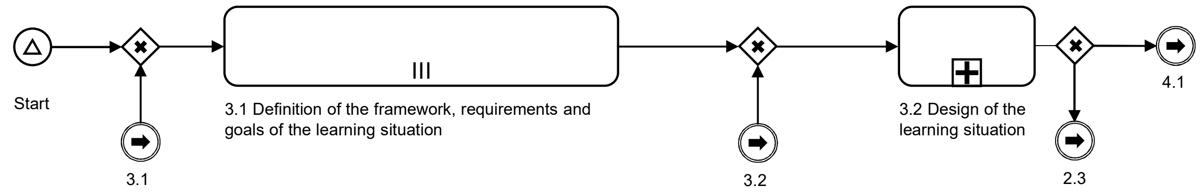

Figure 44: Design of the micro level (learning situation) (based on Tisch 2018, p. 119)[13]

For each formulated competence considering its consisting elements, learning situations were elaborated throughout this research study. Selected key-elements and situations are described in more detail in following sections. Exemplary brief descriptions of elaborated learning situations are outlined in Appendix C. Table 33 summarizes conducted steps on the micro level and refers to respective sections of this thesis.

Table 33: Conducted steps on the micro level throughout this research
(based on Tisch 2018, pp. 155–158)

Step	**Target**	**Remarks to this research study**
Definition of the framework, requirements and goals of the learning situation	- Assignment of practical learning factory elements to concrete learning situations - Detailed definition of single learning situations (based 'sequencing' on meso level)	- Practical learning factory elements are developed based on derived learning objectives requirements (meso level) - Separated learning situations ('exercises') are defined based on operationalized learning objectives (meso level) - see chapter 5.4 - Developed learning factory elements are linked with defined learning situations (see chapter 5.4)
Design of the learning situation	- Design of experimentation and exploitation phases - Design of systematization phases - Design of reflection phases	- Chapter 5.4 provides an overview of defined learning situations and respective strategies of the learning processes - Selected learning situations including different learning strategy phases are introduced in chapter 5.4

All steps throughout the development of the intended training to develop competences of how to design an agile operations system were conducted in an iterative manner. The applied action research approach additionally promotes further development through successive phases of development, testing, evaluation and further development. However, as previously stated, the sections to which reference has been made (conducted steps on macro-, meso- and micro level) represents the final results. The developed (and further developed) learning situations were tested at Graz University of Technology's LEAD Factory in the course of this research study (see chapter 6).

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[13] As proposed by *Tisch 2018* - BPMN 2.0 is used as process notation standard

5.2 Competence 'design of an agile operations system'

This section introduces the formulated competence and its consisting elements central to this thesis. First, this section outlines the approach to competence formulation. Second, it describes exemplarily one key sub-competence. The overview of all formulated elements is presented in Appendix D.

The underlying main competence to be developed through the intended training course is defined as 'professional and methodological competence' (see section 2.3.1) based on consulted literature and the defined research aim and reads as follows:

Participants of the agile operations training are able to design an agile operations system to cope with uncertainty in operations.

As described by *Abele et al. 2015a*, such a competence must be operationalized by means of knowledge aspects and actions. Therefore, the author proposes a classification into 'observable actions', 'professional knowledge' and 'conceptual knowledge' (see following Figure 45) based on the knowledge model by *Renkl 2008*. Professional knowledge contains factual knowledge ('what') and process knowledge ('how', 'when'). Conceptual knowledge aims especially to answer the question of 'why'. (Abele et al. 2015a, p. 34)

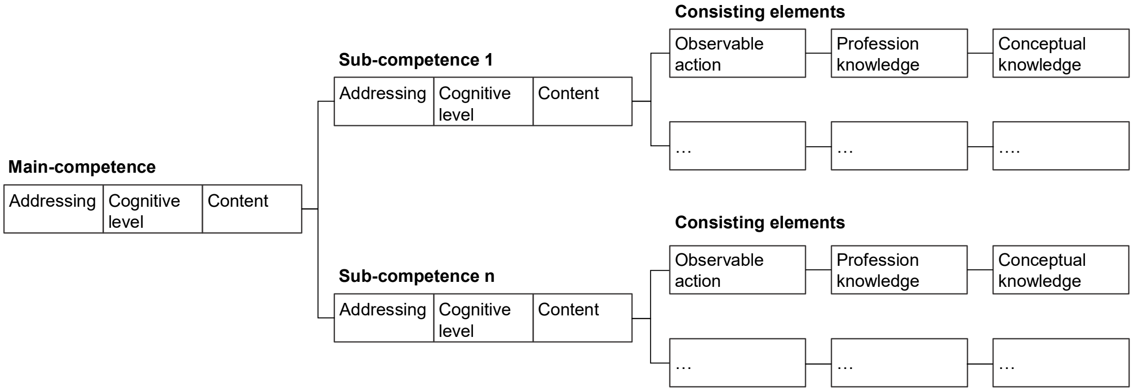

Figure 45: Competence matrix (based on Glass and Metternich 2020, p. 39)

As proposed by *Tisch 2018*, specific key words for competence formulation from *Anderson 2001* ('a taxonomy for learning, teaching and assessing) were used (Tisch 2018, pp. 126-127). These consisting elements are seen in this research study as the most detailed level of 'learning objectives' and form the basis for the further steps of the training course development (derivation of requirements for the learning environment, assessment of learnings).

As stated in chapter 2.6, to the best knowledge of the author of this thesis there is no research addressing the issue of competence development regarding the design of an agile operations system. *Tisch 2018* describes as one possibility to formulate competences to: (Tisch 2018, p. 142; Tisch et al. 2015a, p. 1364)

(1) identify knowledge elements in literature;
(2) derive observable actions out of knowledge elements; and
(3) derive implicit underlying competencies.

Therefore, to derive the consisting elements of the defined main competence, following approach was chosen:

(1) literature review concerning the identification of necessary competences of agile operations and concepts to cope with uncertainty in operations;
(2) breakdown of the underlying 'corporate agility system' into its core elements (see section 2.2.6); and
(3) competence formulation and modularization. This process was carried out in an iterative manner.

The considered main elements necessary to design an agile operations system are: (1) external change driver; (2) monitoring; (3) strategic alignment; and (4) governance (see section 2.2.6). These elements form the sub-competences ('modularization') and observable actions as well as knowledge elements are assigned to each core element.

A structured literature search aimed to identify competences related to coping with uncertainties in operations. The conducted literature search was performed on the Scopus database and was based on a search query. In order to get a broader view on the intended result, alternative approaches (to 'agile operations') and synonyms to the term 'competence' were included in the query (as proposed by Kitchenham 2004, p. 8). In addition, these two search categories were combined with the term 'training' (and synonyms) to focus the search. The search query used the word stem of each term (e.g. 'agil*' instead of 'agility') and considered any sensible combination of the terms across the three categories. In an iterative approach, preliminary searches were conducted to identify existing literature reviews, related terms and the volume of possible relevant research work (Kitchenham 2004, pp. 7–8). Further limitations to the search string were defined based on the preliminary search. Figure 46 shows further limitations of the literature search. The search considered title, abstract and keywords in a time period from 2002 to 2020.

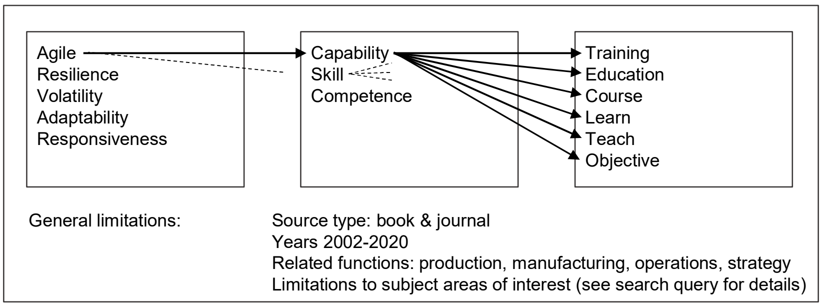

Figure 46: Literature search query (own illustration)

The search resulted in 958 publications. To identify relevant literature, abstracts and if necessary full text were reviewed. The review of the resulting 56 relevant open access studies led to additional 13 full papers considered as secondary literature. Relevant to this research are research studies discussing knowledge elements ('what', 'how', when') of defined core elements of agile operations in the context of this research. The identified knowledge elements were assigned to the identified core elements of the underlying corporate agility system. Then, observable actions and sub-competencies were formulated in an iterative approach.

Figure 47 shows the resulting sub-competencies of the aimed main competence. Further, it depicts the modularization of the developed training course.

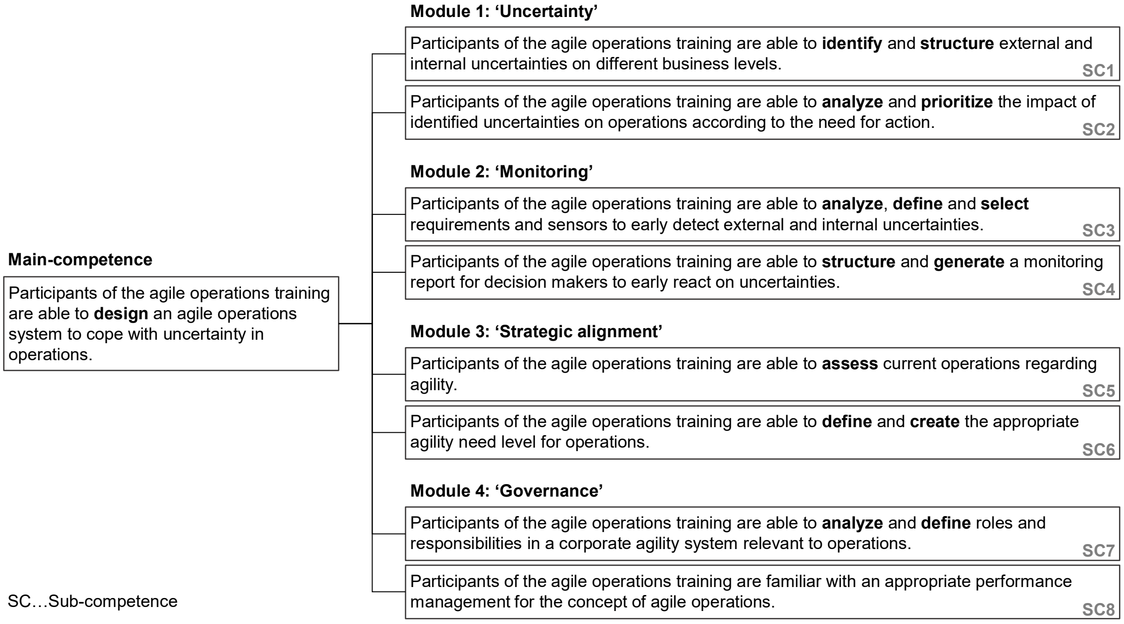

Figure 47: Overview of resulting sub-competences

As previously described, basis for the formulated sub-competences are knowledge elements identified in literature. The following table lists the consisting elements (knowledge elements and observable actions) of the sub-competence 1.

Table 34: Consisting elements of sub-competence 1 (module 'uncertainty')

Observable action	**Professional knowledge ('what', 'when', 'how')**	**Conceptual knowledge ('why')**	**Considered research (knowledge elements)**
- Participants experience uncertainties and their impact on operations (with different viewpoints – e.g. operations manager) - Participants identify possible uncertainties on different areas of origin for the learning factory embedded case using appropriate tools - Participants structure the identified uncertainties according to their characteristics (impact on operations)	- Types of uncertainties and related basic terms - Origin areas of uncertainties - Application of tools to structure uncertainties on different origin areas (e.g. Ishikawa diagram, Porter's 5 Forces, PESTEL analysis)	- Different types of uncertainties influence the potential effect on operations and business - Classification of uncertainties within the business environment according to areas of origin is important for a systematic identification of uncertainties - Why understanding current developments of uncertainties is important for business success (increasing volatility, complex interrelationships, uncertain developments --> uncertainty as new normal)	*Ramsauer et al. 2017*; *Ramesh and Devadasan 2007*; *Irfan et al. 2019*; *Christopher et al. 2004*; *Kleindorfer and Saad 2005*; *Zhang and Sharifi 2000*; *Shan et al. 2013*; *Grøtan and Paltrinieri 2016*; *Sahebjamnia et al. 2018*; *Cheese 2016*

Similar, Table 35 illustrates the consisting elements of the sub-competence 2.

Table 35: Consisting elements of sub-competence 2 (module 'uncertainty')

Observable action	Professional knowledge ('what', 'when', 'how')	Conceptual knowledge ('why')	Considered research (knowledge elements)
- Participants discuss the impact of the experienced uncertainties - Participants estimate the probability of occurrence, the response capability and the impact on the as-is state of the learning factory embedded case for the identified uncertainties - Participants formulate negative as well as positive implications of uncertainties - Participants derive a "probability impact matrix" to prioritize need for action	- Possible effects and characteristic of uncertainties on operations - How to use the tool "Probability impact matrix" to define and visualize the need for action based on the possibility of occurrence and the impact of uncertainties on operations	- Understanding the characteristics and effects of uncertainties on operations is important in order to estimate the impact and to prepare counter measures. - Uncertainties entail risks but also opportunities for companies	*Ramsauer et al. 2017*; *Ramesh and Devadasan 2007*; *Kleindorfer and Saad 2005*; *Zhang and Sharifi 2000*; *Sahebjamnia et al. 2018*; *Cheese 2016*; *Hamad and Yozgat 2017*; *Vagnoni and Khoddami 2016*; *Vecchiato 2015*; *Teece 2007*; *Yang and Liu 2012*; *Wilson 2004*; *Paek and Lee 2018*

Appendix D illustrates the total competence matrix. As previously described, the results from the competence formulation are the basis for (1) derivation of requirements for the learning environment - see chapter 5.3; (2) elaboration of learning situations ('exercises', 'learning factory extensions') – see chapters 5.3 & 5.4; and (3) elaboration of data collection methods - see section 4.4.2.

Roles and responsibilities to design (and implement) an agile operations system

The broad scope of the concept of agile operations and its multidisciplinarity (see chapter 2) underscore agile operations' cross-functionality. Further, as outlined in section 2.2.5, the concept of agile operations is applicable in different industries (Prange and Heracleous 2018, p. 4) and it is situation specific for each company (James-Moore 1997, p. 2). Therefore, practitioners emphasize a coordinated and cross-functional approach using resources across the company when it comes to design and implement an agile operations system (Barriball et al. 2020, 7; Doheny et al. 2012, p. 3). However, the author of this research study could not identify literature describing roles and responsibilities concerning these aspects. Therefore, the author postulates following basic roles and responsibilities based on the consulted literature (see chapter 2.2), the chosen corporate agility system as underlying agile operations framework (see section 2.2.5), and the formulated sub-competences.

- **Responsible role for monitoring**:
  - Focus: change drivers
  - Responsible for 'understanding' the business environment
- **Responsible role for operations:**
  - Focus: agile operations levers
  - Responsible for the elaboration of suitable countermeasures across the value chain
- **Responsible role for governance:**
  - Focus: coordination
  - Responsible for embedding agile operations activities in overall corporate strategy and organization

Despite the individual foci and objectives, the design of an agile operations system (as well its implementation) requires a close coordination of proposed responsibilities due to the high amount of interdependences. Figure 48 depicts the described roles and responsibilities.

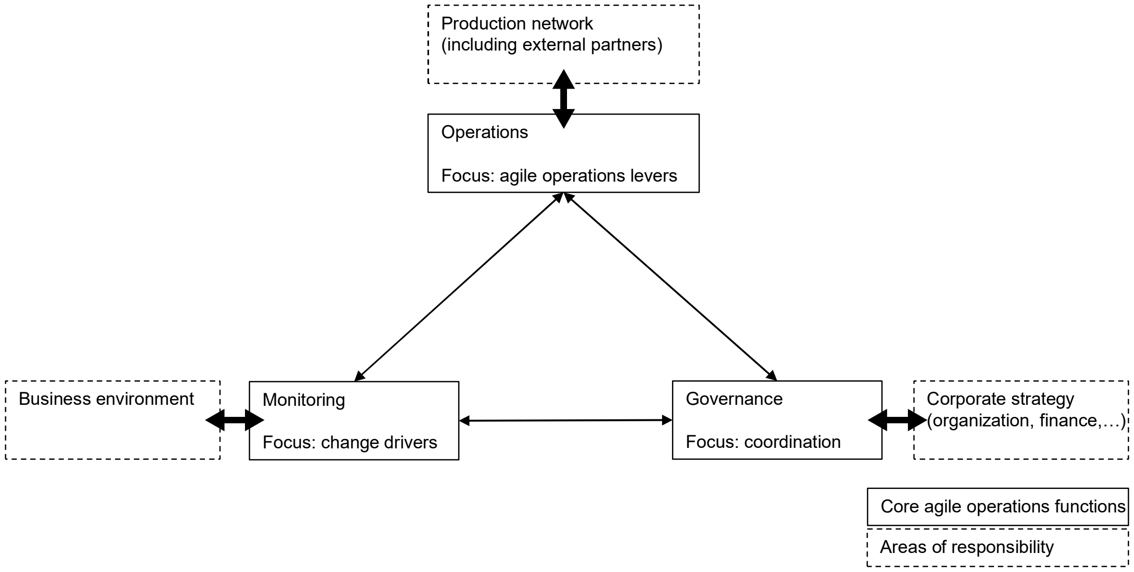

Figure 48: Roles and responsibilities to design an agile operations system (own illustration)

However, the author of this research does not claim general validity of these responsibilities. Above all, the enumeration does not pre-scribe the amount or actual position within the organization of involved experts as priorities and boundary conditions differ from case to case. However, as stated in section 2.2.8, consulted literature points out, that such projects are *"[...] first and foremost a responsibility of management."* (Wiendahl et al. 2015, p. 109)

The focus of this research study lies on the design of an agile operations system and not on its implementation as visible at the formulated main competence. However, formulated sub-competences contain partly elements as well necessary for implementation. This includes e.g. the generation of a monitoring report, the definition and creation of agile operations levers or the selection of lever combinations. Further, the learning factory principle emphasizes implementation activities as participants are encouraged to implement their own solutions to identified problems. However, this research does not claim to develop necessary competences to implement an agile operations system as more generic competences are necessary (e.g. communication, project management, change management).

5.3 Requirements for the learning environment and initial solution approaches

Tisch 2018 proposed to define requirements based on factory levels and the depicted production processes of the learning factory (Tisch 2018, pp. 128-129). As previously described, the research aim of this thesis is to extend an existing learning factory to map the subject matter of agile operations. The baseline for potential necessary additional requirements is the narrow definition of a learning factory by *Abele 2018* (see section 2.4.1). This presupposes that at least an existing physical product processed on multiple stations, technical and organizational aspects and a changeable setting to enable at least two maturity setups exist (Abele 2018). The assumed minimum characteristics of an existing learning factory are shown in a learning factory morphology (as proposed by *Tisch et al. 2015b*) in Appendix E.

The following three tables show the derived requirements to the learning environment based on elements of the formulated competence to design an agile operations system. For each sub-competence were requirements derived regarding the factory level (network, plant, segment, system, cell, and workstation), a surrounding business environment and the product processed. Further, the considerations included learnings from basic literature (see chapter 2.2).

Table 36: Requirements from SC1, SC2, SC3 & SC4 for the learning environment

SC	Business environment	Network	Plant	Segment System Cell	Workstation	Product
SC 1 & SC 2	- Information about suppliers for different raw materials/sub components (incl. price, lead-time, etc.) - Customer analysis - Information about strategy and vision - Customer orders - Predefined external and internal uncertainties with tangible effects on the performance of the production system	- (Global) production network consisting of different plants across the value chain - Information about plant production programs - Information about plant locations - Information about logistics-inbound & outbound (e.g. type of transport, duration,)	- Abstraction of a real-life company structure including core functions (purchasing, operations, general management, etc.) - As-is state (improvable) abstraction of corporate processes & organizational structure including several hierarchical levels - Different roles with predefined job descriptions to cover the aspects operations, supplier and customers within the business environment	- Lean production implemented (value stream, Kanban, etc.) - Possibility to change production schedule - Inventory designed in such a way that a bottleneck occurs with no reordering for different components - System/work cell designed that external or internal uncertainties influence the output	- Connected assembly and/or manufacturing work stations to produce products - Lean production implemented (e.g. 5S, standard operating procedure) - Spatially separated areas of work (work stations) for supply chain, customer, management/leadership and production	- Physical product - At least 2-3 different product variants to increase complexity
SC 3 & SC 4	Trackable "information via the monitoring system about possible uncertainties suitable for the business environment surrounding the learning factory product(s) - e.g. inbound logistics, supplier and customer side		Abstraction of a real-life company structure including core functions (purchasing, operations, general management, etc.)	-	- Working monitoring system to simulate information gathering to early detect uncertainties (external & internal) - Monitoring system must be adjustable by participants (e.g. keywords, source of information) - Monitoring system must be connected to information defined ad hoc by the trainer based on participants results (identified uncertainties, etc.)	Physical product with enough complexity to create a connected and distributed business environment - e.g. different raw materials, sub-components from different industries, supply chain spread across continents

SC...Sub-competence

Table 37: Requirements from SC5 & SC6 for the learning environment

SC	Business environment	Network	Plant	Segment	System	Cell	Workstation	Product
SC 5	-	- (Global) production network consisting of different plants across the value chain - Information about plant production programs - Information about plant locations - Information about logistics-inbound & outbound (e.g. type of transport, duration)	Potential impact of identified uncertainties on the current learning environment (from different company function to production and a single work station)					"New" product to be implemented - difference in part dimensions, raw material, necessary tools, etc.
SC 6	- Information about suppliers for different raw materials/sub components (incl. price, lead-time, etc.) - Customer analysis - Information about strategy and vision - Customer orders - Predefined external and internal "uncertainties" with tangible effects on the performance of the production system	- Information about the strategic objectives of the learning factory surrounding company on .Business strategy .Production program .Operations strategy etc. - Detailed formulated agile operations levers to counteract uncertainties on network level implementable at the learning environment(incl. different levels of levers)	Detailed formulated agile operations levers to counteract uncertainties of core company functions (e.g. purchasing, R&D) implementable at the learning environment (incl. different levels of levers)	Detailed formulated agile operations levers to counteract impact of uncertainties on production (e.g. short term production program change, possibility of multiple takt-times) implementable at the learning environment (incl. different levels of levers)				Physical product with enough complexity to create a connected and distributed business environment - e.g. different raw materials, sub-components from different industries, supply chain spread across continents

SC...Sub-competence

Table 38: Requirements from SC7 & SC8 for the learning environment

SC	Business environment	Network	Plant	Segment	System	Cell	Workstation	Product
SC 7	- Information about suppliers for different raw materials/sub components (incl. price, lead-time, etc.) - Customer analysis - Information about strategy and vision - Customer orders - Predefined external and internal uncertainties with tangible effects on the performance of the production system	- (Global) production network consisting of different plants across the value chain - Information about plant production programs - Information about plant locations - Information about logistics-inbound & outbound (e.g. type of transport, duration)	- As-is state (improvable) abstraction of corporate processes & organizational structure including several hierarchical levels - Provide information to enable participants to define to-be state job descriptions to cover the aspects operations, supplier and customers within the business environment	Production system (see requirements formulated for SC1, SC2) enabling predefined external and internal uncertainties to have impact on the performance of the production system to stress the defined organizational structure and processes of participants				- Physical product - At least 2 different products - At least 2-3 different product variants - Product with enough complexity to create a connected and distributed business environment - e.g. different raw materials, sub-components from different industries, supply chain spread across continents
SC 8	-		- Potential impact of identified uncertainties on the current learning environment (from different company function to production and a single work station) - Production system (see requirements formulated for module 'uncertainty') enabling predefined external and internal uncertainties to have impact on the performance of the production system to stress the defined organizational structure and processes of participants - Defined, meaningful and measurable KPIs to evaluate agile operations activities and its impact on the transition from the as-is state to the to-be state of the learning environment					

SC…Sub-competence

The following passages summarize the main derived requirements along with the identified limitations of learning factories in the literature (see section 2.4.5).

First, the **resources-related limitation** needs to be addressed. Building and operating a learning factory is resource intensive in terms of cost, personnel and space (Tisch and Metternich 2017, p. 93). Hence, the requirements to include e.g. value chain aspects into existing learning factories need to consider resource feasibility. Consulted literature points out that this limitation applies especially to the mapping of upper factory levels (e.g. production networks) (Lanza et al. 2015, p. 121). In the case of agile operations this relates to derived requirements regarding production network aspects, supply chain and business environment developments, related agile operations levers to counteract uncertainties on all factory levels as well as a space related requirement of separated production (learning factory) and management office areas (e.g. purchasing, sales).

Second, as *Abele et al. 2019* point out, **time-related limitations** occur when participants' actions do not cause immediate feedback in the learning environment. The learning factory principle cannot be used easily to map e.g. longer-term strategic decisions without a 'fast-forward' mechanism to allow timely feedback. (Abele et al. 2019, p. 287)
In relation to this research study, this applies especially to the impact of e.g. uncertainties in customer behavior, in- and outbound logistic or supply chain disruptions and similar 'black swan' events on the learning factory itself. Further, strategic aspects of agile operations to counteract uncertainties relate to this time related limitations of learning factories.

Third, connected to time related limitations are the **solution-related limitations**. These limitations address the need concerning the possibility for participants to directly implement their derived solutions at the learning environment (Abele et al. 2019, p. 287). As previously stated, the learning factory principle requires at least two different pre-defined maturity setups (from deliberately suboptimal setup to an optimized target state). In addition, solutions developed by participants should be largely implementable. Hence, the topic of agile operations relates to these limitations especially concerning the monitoring system to sense external developments, governance related aspects such as restructuring hierarchical levels and responsibilities or implementing appropriate agile operations levers.

Further, the topic of agile operations requires characteristics concerning the **product** processed at the learning factory. As consulted literature points out, criteria to select a learning factory product contain e.g. the ability to map several stages of the value chain or didactic factors such as the match of the product with the learning content (Küsters 2018, p. 140). Derived requirements address the availability of several product variants to increase complexity (e.g. inventory, order scheduling, supply chain) and the availability of an additional product with differences in e.g. part dimensions, employee qualification or required tools.

Initial solution approaches

Previous identified and described related studies to this research (see section 2.5.1) provide possible solution strategies to overcome the identified limitations of learning factories. The conducted review of related studies showed that *Reiner 2009* and *Küsters 2018* implemented a fictional case study to link corporate goals to shopfloor learning factory actions. *Riffelmacher 2013* confronted participants with new problem situations (e.g. machine disruption) via scenario-based learning. *Faatz 2017* applied a discrete event simulation to teach tool management as an approach to close the feedback loop of participant's actions and timely response. This approach enabled participants to experience the long-term impact of their actions and experimenting with different tactics to solutions. *Küsters 2018* implemented parts of a role-play to take on different viewpoints of digitalization in operations.

In addition, *Thiede et al. 2017* provide a framework to cluster requirements of learning content according to time aspects and necessary implementation effort (see Figure 49). Time aspects address (1) necessary time for participants to carry out the intended actions and (2) feedback time until participants experience the effect. The implementation effort addresses resource related limitations like costs and technical feasibility. The framework consists of four clusters: (A) physical acting with immediate real time feedback (e.g. implementing 5S); (B) physical acting with simulated effects (e.g. fictional case study as link to corporate goals); (C) virtual acting with real time implications (unfeasible physical action due to e.g. technical limits) and (D) virtual acting with simulated implications (e.g. discrete event simulation for tool management – see *Faatz 2017*). (Thiede et al. 2017, pp. 240–241)

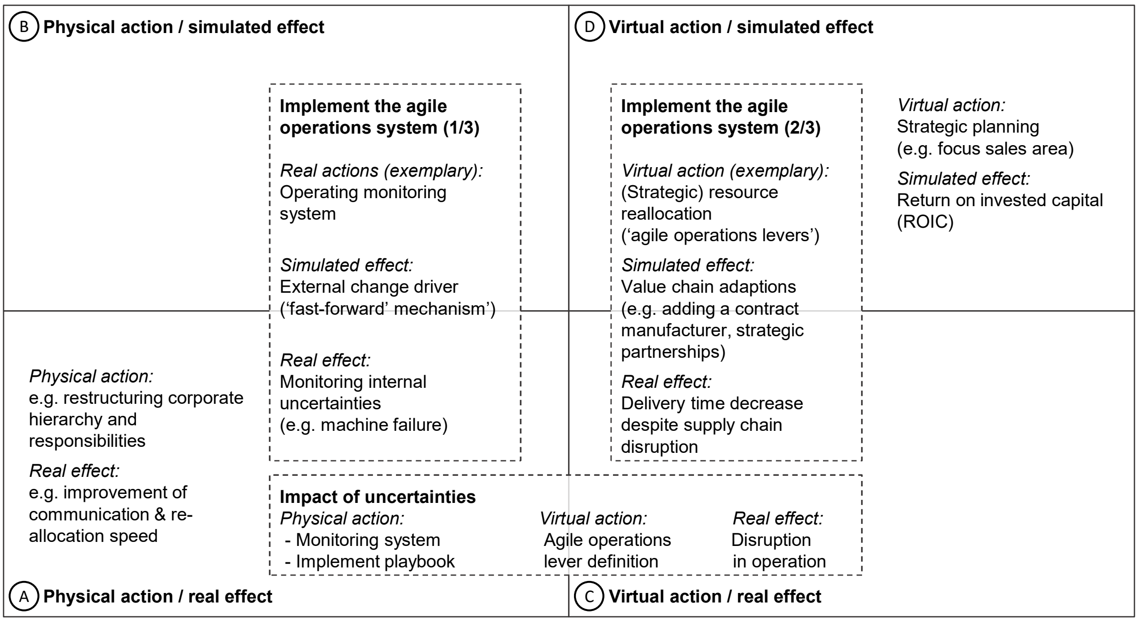

Figure 49: Strategies to extend learning factories for agile operations
(adapted from Thiede et al. 2017, p. 240)

Figure 50 shows the classification of selected actions when designing and implementing an agile operations system according to the framework proposed by *Thiede et al. 2017*. The resulting classification also provides the strategic direction for the initial solution approaches of this research (see chapters 5.4 and 5.5). The mapping of agile operations affects all segments proposed by *Thiede et al. 2017* due to time- and resource-related (technical and economic feasibility) issues. Consequently, an agile operations system requires virtual extensions to a learning factory as well as a simulation as 'fast-forward' mechanism. The term 'hybrid learning factory' describes the combination of physical learning factory and virtual extensions (e.g. Abele et al. 2019, p. 307).

Thiede et al. 2017 highlight the potential of virtual extensions to include additional competences to learning factories with only a small physical setup. Such virtual extension enables e.g. the mapping of internal administrative functions or surrounding business elements (e.g. customer behavior). The authors suggest in contrast to the work by *Faatz 2017* a close interrelationship in-between physical setup and virtual extension. In addition, *Thiede et al.* propose a concept of a business game to enable the interplay of virtual actions and a combination of simulated and real effects (see Figure 50). (Thiede et al. 2017, pp. 241–243)

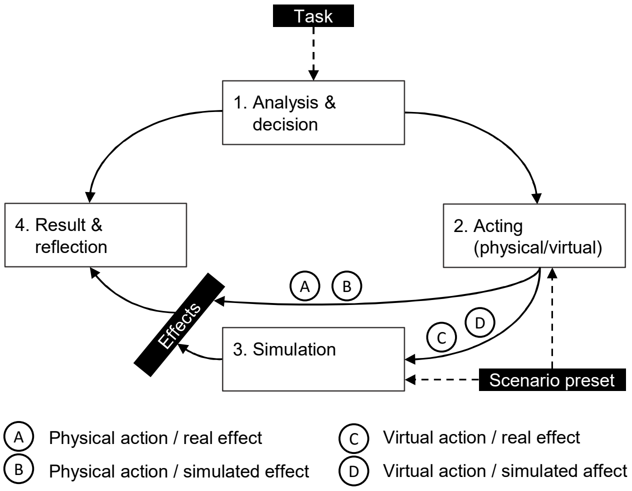

Figure 50: Concept to combine physical and virtual actions, simulation and corresponding results (based on Thiede et al. 2017, p. 243)

The author of the present research realizes in such a solution approach the potential to fulfill requirements of agile operations on a learning environment with feasible resource input. Therefore, such a solution approach has a central role in the further course of this research work. However, *Abele et al. 2019* point out that such deviations from the learning factory principle threaten to reduce the learning process effectiveness (Abele et al. 2019, p. 91). The interface in-between physical setup and virtual elements therefore requires careful alignment (Abele et al. 2019, pp. 455–456).

5.4 Sequencing and learning activities in detail

Tisch 2018 describes a sequence of a training course as learning process within a learning module. Sequences address a sub-competence or are defined in terms of specific actions and contain several learning activities. Learning activities are planed elements with either introductive, systemizing, explorative, experimental or reflective/generalizing character (see sections 2.3.3 and 2.4.2). (Tisch 2018, pp. 144-152)
Following three different strategies to design a learning sequence exist: (Tisch et al. 2015a, p. 1365)

- Problem pull:
  Exploration (problem occur) - *systematization* (theory input) - *experimentation* (problem solving/testing) - *reflection* (discussion, feedback)
- Theory push:
  Systematization (theory input) - *experimentation* (problem solving/testing) - *reflection* (discussion, feedback)
- Reflection first:
  Reflection (discussion based on e.g. previous experiences) - continue with strategy ‘problem pull’ or ‘theory push’

These strategies apply at the most detailed level of course planning (learning situations – micro level). On a higher-level, the derived sub-competences provide the general structure of the course. However, related studies showed, that a clear guiding procedure to follow throughout the course supports the learning process of participants (e.g. Gossmann and Nyhuis 2012, p. 2186). Thus, before developing learning activities on a detailed level, this research study defines in the following a basic implementation procedure. As previously described, few implementation procedures on an operational level for the concept of agile operations exist (see e.g. Rabitsch and Ramsauer 2015, p. 2). Further, it is not the objective of this research to develop and validate such a guiding procedure (see chapter 3). The aim is to provide a simplified and easy understandable step-by-step procedure for implementation to increase learning effectiveness for the participants.

In operations management several standardized and well-known process methodologies like PDSA[14] (Deming 2000, p. 132), TOC[15] (Goldratt 1990, p. 8) or DMAIC[16] (Lunau 2009, p. 10) exist (for a comparison see e.g. Hammer 2017, p. 121). The author of this research chose the DMAIC process methodology as basis. Literature points out that DMAIC is “*[…] the structured methodology and industry-accepted universal language of improvement.*” (Burton 2011, p. 53).

Slack et al. 2010 defines the phases of the DMAIC cycle as follows: (Slack et al. 2010, p. 545)

- **Define** - Understanding the nature of the problem to identify the scope and to define the requirements of the necessary improvement
- **Measure** - Measurement of the actual situation, validating and refining the problem by the usage of data

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[14] Plan-do-study-act

[15] Identify the constraint-explore the constraint-subordinate the process-elevate the process-repeat

[16] Define-measure-analyze-improve-control

- **Analyze** - Identification of the problem root causes
- **Improve** - Elaboration, testing and implementation of solutions to remove root causes. Results are measured
- **Control** – Continuous monitoring of the improvement

The author of this research adapted this standard process according to the identified sub-competences. The elaborated process provides the general sequence of the training course to guide participants and is shown in following Figure 51.

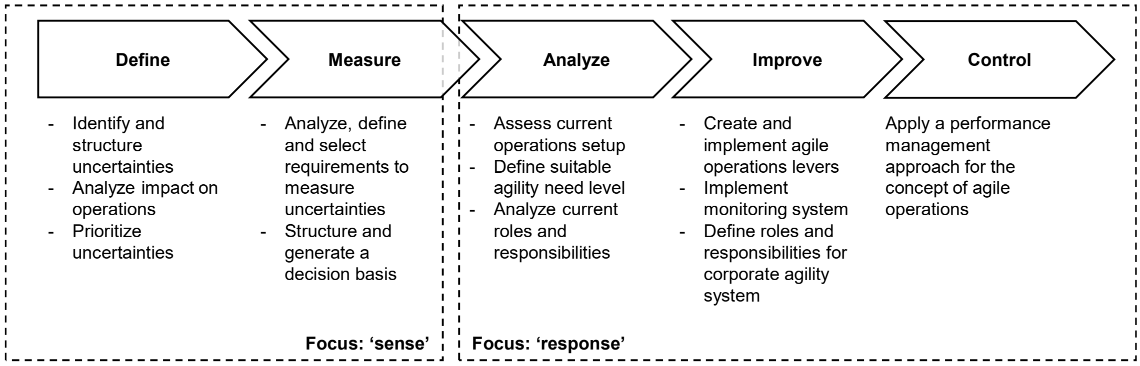


Figure 51: Overview of the applied guiding procedure throughout the training course

The elaboration of the course sequences including the learning activities is based on the derived learning modules, formulated sub-competences, the proposed guiding procedure to implement agile operations, derived requirements to the learning factory environment and the introduced initial solution approaches. This research study considered the application of the learning activities (combination, order, etc.) (as proposed by Tisch 2018, pp. 144-148). The following tables provide the final results (including further improvements of the course throughout action research cycle 2) of developed learning sequences. Table 39 shows the learning sequences ('exercises') for the modules 1 ('uncertainty') and 2 ('monitoring').

Throughout **exercise #1** participants explore the non-agile as-is-state from the viewpoint ('roles') of operators, operations managers, purchasing managers, and general management. Participants experience external and internal uncertainties (see section 2.2.6– types of uncertainties) and their impact on operations (see section 5.5.1 for more details).

Exercise #2 addresses the structured identification of uncertainties on different business levels by applying the tools 'Ishikawa diagram', 'Porter's 5 forces' and the 'PESTEL analysis' (as proposed by e.g. Romeike and Finke 2003, pp. XV–XVI). Further, participants classify the identified uncertainties based on their effect on operations (as outlined by Kremsmayr 2017, p. 55 - see section 2.2.6).

Finally, in **exercise #3** participants assess identified uncertainties according to the need for action using a 'Probability-Impact Matrix' (as proposed by e.g. Romeike and Finke 2003, p. 141) to illustrate results. As agile operations aims to enhance the economic situation on both, upswing and downswing situations (Rabitsch and Ramsauer 2015, p. 2), emphasis is always put on potential positive as well as negative effects of uncertainties.

Table 39: Overview of the resulting learning sequences of module 1 'uncertainty' and module 2 'monitoring'

	Introduction	**Systematization**	**Experimentation**	**Exploitation**	**Systematization**	**Reflection**
Exercise #1 "create awareness"	- Current industry challenges (Volatility, globalization, etc.) - Definition of the concept of agile operations - Industry example	-	-	- Abstraction of a real-life company structure including core functions (purchasing, operations, general management) - Participants experience exemplary occurring (external) disturbances on operations during running the learning factory operation	Elaboration of a timeline of events and impact of uncertainties/ disturbances on operations	- Discussion about different roles, actions and challenges - Reflections of timeline of events & impact of uncertainties on operations
Exercise #2 "understand uncertainties A-identification"	- Global trends influencing uncertainty in business environments - Characteristics of uncertainties	- Levels of uncertainties (macro, micro and company level) - Effects of uncertainties on operations	- Participants identify possible uncertainties on different levels for the given learning factory embedded case using tools like Ishikawa Diagram, PESTEL Analysis and Porter's 5 Forces - Participants classify the identified uncertainties according to their effects on operations	-	-	- Recap of Exercises #1 & #2 and classification of experienced uncertainties - Group presentations: identified uncertainties and effects on operations
Exercise #3 "understand uncertainties B-prioritization"	Introduction concerning the challenge of responsiveness and related questions to be answered	- Presentation of a basic assessment tool from risk management - Probability-Impact Matrix to display results	- Participants estimate probability of occurrence and the need for action for prior identified uncertainties - Formulation of negative as well as positive effects of prioritized uncertainties - Elaborate Probability-Impact Matrix	-	-	Group presentation and discussion about elaborated Probability-Impact Matrix
Exercise #4 "monitoring"	- Basic terms are explained (e.g. types of information, types of sensors) - Benefit of monitoring with reference to Exercises #1 & #3 - Dependencies of monitoring system and agile operations	- Procedure to set-up a monitoring system - Typical monitoring fields and corresponding potential objectives and exemplary data sources - Tool "Fault tree analysis", “monitoring report”	- Participants elaborate a fault tree - Definition of corresponding trigger points (keywords, etc.) - Elaboration of a monitoring plan - Participants set-up a monitoring system at the learning factory based on prior work - Participants test the implemented monitoring system (Can intended uncertainties be detected?)	-	-	Recap of Exercise #1 / Exercise #4 and discussion about the potential impact of a monitoring system on operations

Exercise #4 ‘monitoring’ builds on derived results of the previous exercises. Theoretical input is mainly based on a step-by-step implementation process proposed by *Heldmann 2017*. Further, the learning activity ‘systematization’ contains examples of typical monitoring fields of industrial companies and selected types of ‘sensors’. Participants use the tool ‘fault tree analysis’ (as proposed e.g. by Romeike and Finke 2003, pp. 263–265) to identify sources and to define suitable sensors for identified and assessed uncertainties. Finally, participants set-up and test a working monitoring system at the learning factory (see section 5.5.3).

Exercise #4 was further developed based on results of the action research cycle 1. Especially the pre-post knowledge test did not show a sufficient increase in participants knowledge development (‘benefit of a monitoring tool concerning an agile operations system’). Therefore, the exercise was extended (fault tree analyses), a best-practice industry example was included and the reflective actions were improved (see section 6.4.1).

Table 40 shows exercises of teaching module 3 ‘strategic alignment’. Throughout **exercise #5** participants explore potential lever categories (‘agile operations lever categories’ – see section 2.2.6) to identify and structure necessary adaptions in operations. This is enabled by adding a new product (differences in part dimensions, raw material, necessary tools, …) to the existing learning factory production line.

Exercise #5 was developed based on results of action research cycle 1. Especially the conducted questionnaire and the observation of intermediate results emphasized the development of an additional hands-on exercise to explore agile operations lever categories (see section 6.3.2).

Based on the identified high-level agile operations categories participants rate the current operations system (including the impact of the surrounding business landscape) in **exercise #6** based on their experiences from previous exercises. As described in section 2.2.6, several approaches to measure agility exist (Sherehiy et al. 2007, p. 449). The author of this study decided to apply an (simplified) index approach (see e.g. *Ren et al. 2000).*

A second main step to employ agility is the identification of needed agility levers (Sharifi and Zhang 2001, p. 775). **Exercise 7** aims to elaborate suitable agility levers for the learning factory embedded case. As highlighted in section 2.2.6, several levers across the operations domain need to be leveraged in parallel (Brown and Bessant 2003, p. 725). Therefore, participants need to understand that especially interactions of levers are crucial for the overall result (Eppinger and Browning 2012, pp. 133–134). This is enabled by the application of a Design-Structure-Matrix (see e.g. *Eppinger and Browning 2012*). Further, participants have to choose suitable lever combinaitons (using previously identified by them) to cope with two given scenarios.

Participants define throughout **exercise 8** an appropriate agility need level based on the current setup, a given corporate strategy for the learning factory embedded company and previous exercise results. The application of the same index approach as in exercise 6 to define the target agility need level results in a gap in-between the current and targeted situation. This gap needs to be addressed by appropriate countermeasures - ‘agile operations levers’ - see section 2.2.6. Therefore, participants (in groups) choose suitable lever combinations for the learning factory case in a business game approach (see section 5.5.4).

Table 40: Overview of the resulting learning sequences of module 3 'strategic alignment'

	Introduction	Systematization	Experimentation	Exploitation	Systematization	Reflection
Exercise #5 "adapt operations – new product"	Presentation of the "new" product to be implemented	-	-	Participants identify necessary adaptions to the production system due to e.g. differences in part dimensions, raw material, necessary tools, etc.	Elaboration of high-level categories of identified adaption	Group presentation and discussion about elaborated categories and their meaning for the agile operations concept
Exercise #6 "rate current system - agility index"	Introduction to strategic alignment and basic steps to choose an appropriate level of agility	- Explanation of the "Agility index" tool to assess the current operations setup - Practical example of an agility index from automotive industry	Rate the current setup of the learning factory (and surrounding case) based on experiences from previous exercises.	-	-	Group presentations and discussion about the elaborated agility index
Exercise #7 "create agility – lever identification"	- Definition and context of the term 'agile operations lever' - Basics of scenario planning	- Best practice examples of agile operations levers (brief description and different levels of agility) for each high-level agile operations category - Design-Structure-Matrix in order to identify dependencies of levers & lever combinations	- Identification of possible agile operations levers - Use a "Design-Structure-Matrix" to show interdependencies among levers - Choose, based on 2 example scenarios planned by participants, an appropriate lever combination to counteract scenario impacts	-	-	- Recap of exercises #1 & #7 and possible impact of identified levers if in place on the first hand - Group presentations and discussions about scenarios planning and used lever combinations to counteract defined scenario examples
Exercise #8 "define agility need level"	Introduction to a stepwise procedure to derive from the corporate strategy an appropriate agility level	- Explanation of the intended operations strategy of the learning factory embedded case using a "Ansoff Matrix" - Detailed agile operations assessment of the learning factory embedded case as baseline	- Definition of future agility level based on assessment of the current setup and strategy using the agile operations business game	-	-	- Participants present their derived agility level and discuss why they choose specific levers and lever combinations - Discussion about the impact of chosen levers in the agile operations business game (see exercise #10)

Table 41 shows the learning sequences related to teaching module 4 'governance' and addresses the respective sub-competences. In **exercise #9** participants re-structure the initial hierarchical and functional responsibilities to support the agile operations system. The re-structuring is based on gained experiences throughout exercise #1, the elaborated monitoring approach and related theory input. Further, to highlight the pro-active approach, an operations' playbook containing coordinated agility levers is elaborated (see section 2.2.6) to react quickly on defined scenarios (elaborated by participants).

Exercise #10 'implement agile operations' addresses performance management approaches to monitor agile operations related activities (Sull 2009b, pp. 151–152). As described in section 2.2.6, consulted literature points out, that four dimensions of change proficiency apply to agility: (1) cost of change; (2) time of change; (3) robustness of change; and (4) scope of change (Dove 1994, p. 3). The author therefore chose a balanced scorecard approach to measure the performance of the designed agile operations system. Finally, the previous elaborated building blocks are put together and participants experience their designed agile operations system hands-on at the learning factory. In a similar approach as in exercise #1, participants explore again uncertainties and their impact on operations now with a working monitoring system, defined agile operations levers, a playbook, adapted hierarchical structures and functional responsibilities in place. In parallel to the hands-on exercise the business game approach enables the simulation of the impact of e.g. agility levers influencing value chain aspects on the overall system (detailed description of the developed business game is available in section 5.5.4). In a final debriefing session, 'real' and 'simulated' effects of the designed agile operations system are discussed in terms of an economic (results of the business game) and a qualitative assessment using the introduced balanced scorecard approach (based on taken action at the physical learning factory).

The developed agile operations business game was significantly further developed based on action research cycle 1. This includes especially the further development of a first applied single result indicator approach to a timeline-based approach in action research cycle 2.

Further general adjustments from action research cycle 1 to cycle 2 contain improvements of e.g. handouts, task descriptions or the increase of time for reflection. In section 6.4.1 are conducted adjustments reasoned (based on collected data) and briefly described. Further, their implication is subjectively assessed by the author in section 6.4.3.

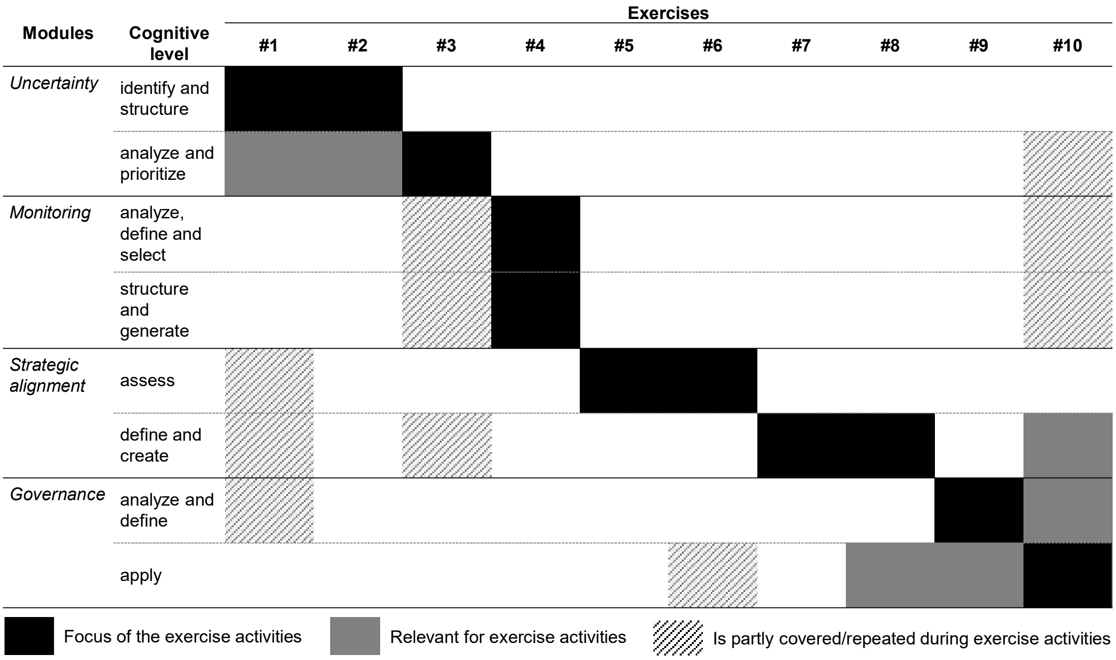
Table 41: Overview of the resulting learning sequences of module 4 'governance'

	Introduction	Systematization	Experimentation	Exploitation	Systematization	Reflection
Exercise #9 "define roles & responsibilities"	Awareness for the importance of organization and culture for the topic of agility	- Introduction to organizational structures enhancing agility - Integrative function for agile operations - Processes to orchestrate agile operations (agility playbook)	- Definition of new roles for the learning factory embedded case roleplay - Elaboration for a playbook based on chosen levers and developed scenarios (based on identified uncertainties)	-	-	- Discussion about the impact of the elaborated playbook - Discussion about the impact of the new defined organizational structure, roles and responsibilities
Exercise #10 "implement agile operations"	Introduction to performance management and scorecards	In detail explanation of a scorecard approach to measure dynamic capabilities	Application of developed agile operations system (developed elements: see previous exercises – e.g. monitoring system, roles & responsibilities, agile operations levers etc.)	Participants experience exemplary occurring (external) disturbances on operations during running the learning factory operation ("to-be state" - see exercise #1)	- Elaboration of a timeline of events and impact of uncertainties/disturbances on operations - Discussion of business game results in combination with hands-on activities	Recap learning factory experiences (as-is state vs. to-be state) using the scorecard approach

The author of this work set further boundary conditions including course duration and a necessary knowledge basis. A time limitation of the overall course duration was defined with two working days, as the target group (beside students) of the developed training course is industrial personnel (as proposed by Tisch et al. 2016, p. 1358). The subject matter of lean production is assumed as a prerequisite for the developed course. Further, the starting point (non agile as-is-state) is defined as a lean state of the learning factory (this ideally includes the existence of elements such as Kanban, Heijunka, etc.). If participants are not familiar with main elements of lean production, an upfront lean training course should be conducted.

To counter a common phenomenon in learning module development, *Suh 2001* cited by *Tisch 2018* suggests, that functional requirements (sub-competencies) be mapped against design parameters (exercises) in a matrix. The matrix gives a good overview of whether (1) sub-competencies are well represented in the learning sequences and (2) if developed learning sequences have a clear focus. (Tisch 2018, pp. 144-148)

Figure 52 illustrates this matrix for the developed training course. The resulting picture shows that each sub-competence is at least once in the focus of a dedicated exercise. Further, it shows the importance of exercise #1 as 'source of experience' for the following exercises as well as exercise #10, where participants experience the targeted agile operations state.



Modules	Cognitive level	Exercises									
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Uncertainty	identify and structure	■	■								
	analyze and prioritize	▓	▓	■							▨
Monitoring	analyze, define and select			▨	■						▨
	structure and generate			▨	■						▨
Strategic alignment	assess	▨				■	■				
	define and create	▨		▨				■	■		▓
Governance	analyze and define	▨								■	▓
	apply						▨		▓	▓	■

■ Focus of the exercise activities ▓ Relevant for exercise activities ▨ Is partly covered/repeated during exercise activities

Figure 52: Overview of addressed sub-competences in developed learning sequences (as proposed by Tisch 2018, pp. 144-148)

This section formulated sub-competences, requirements to the learning environment, introduced initial solution approaches and the developed learning sequences. However, core elements of the agile operations training are not explained in detail. Following chapter 5.5 provides detailed information about core extensions to add the subject matter of agile operations to an existing learning factory.

5.5 Developed learning environment extensions

Initial analysis of potential strategies to extend learning factories for agile operations based on derived requirements (see chapter 5.3), that the content requires virtual actions and simulated effects besides hands-on activities with a timely and physical feedback (see section 5.3). This comprises especially the mapping of different hierarchies, functions and the surrounding business environment, a technical solution for a monitoring system as well as the aforementioned agile operations business game.

The developed core extensions partly refer to the application of the developed training course at Graz University of Technology's LEAD Factory described in chapter 6.1 (e.g. figures, simulated company functions). However, the logic of these extensions can be applied to existing learning factories (concerning minimal requirements of initial learning factory setup see Appendix E). Further, adaptions for different learning factory settings than in this research study might proof valuable depending on e.g. the available infrastructure or the processed product.

5.5.1 Case study: Fictional business environment

The scope of agile operations comprises 'sensing' and 'responding' (see section 2.2.4). Hence, literature points out that a company needs to understand the business environment and emerging uncertainties (Yusof and Aziz 2008, p. 108). This involves the early detection of external change drivers including e.g. competitor's actions, customers demand, technological advancements as well as legal and political changes (Overby et al. 2006, p. 122). Subsequently, participants need to experience such external influences at the learning factory.

Therefore, the author chose a case-method approach to simulate the surrounding environment of the learning factory. A similar approach to simulate the impact of shopfloor activities in a learning factory on the corporate goals was applied by e.g. *Reiner 2009* and *Küsters 2018*. Further, previous positive experiences of the author with the case-method at learning factories (see *Hulla et al. 2019a*) contributed to the initial decision.
In addition, the case-method is combined with aspects of the scenario method. Especially related studies with a focus on changeability (e.g. *Riffelmacher 2013; Gossmann and Nyhuis 2012* - see section 2.5.1) apply different scenarios to confront participants with 'new' problem situations throughout the training course.

Case studies can be defined as "*[...] stories with an educational message.*" (Terry 2012, p. 28) and provide an appropriate amount of information as basis for decision-making (Ellet 2018, p. 12). The scenario-method emphasizes the understanding of interdependencies between system elements (Bonz 2009, 158). Section 2.3.3 describes both experiential learning methods in more detail.

The aim of the fictional business environment is to provide necessary information of key-value chain elements to enable external uncertainties, which influence operations. Tables 39, 40, and 41 in section 5.3 list these minimal required information. Further, the external business environment must be linked to the processed learning factory product and internal processes. Figure 53 shows the 'big picture' of the developed fictional business environment for the application of the agile operations training course at the LEAD Factory (see chapter 6).

The developed business environment contains several suppliers for various parts of the product processed, in-bound logistic information, a fictional assembly line at e.g. China, the physical assembly at the learning factory itself, different sales channels and outbound logistic information. These information are further detailed concerning e.g. volumes (minimal/maximal order size, sales history, forecasts), delivery times (supplier specific), or locations of value network sites. In addition, the strategic focus and global corporate goals are part of the case study to link agile operations to the fictional company (see section 2.2.6).

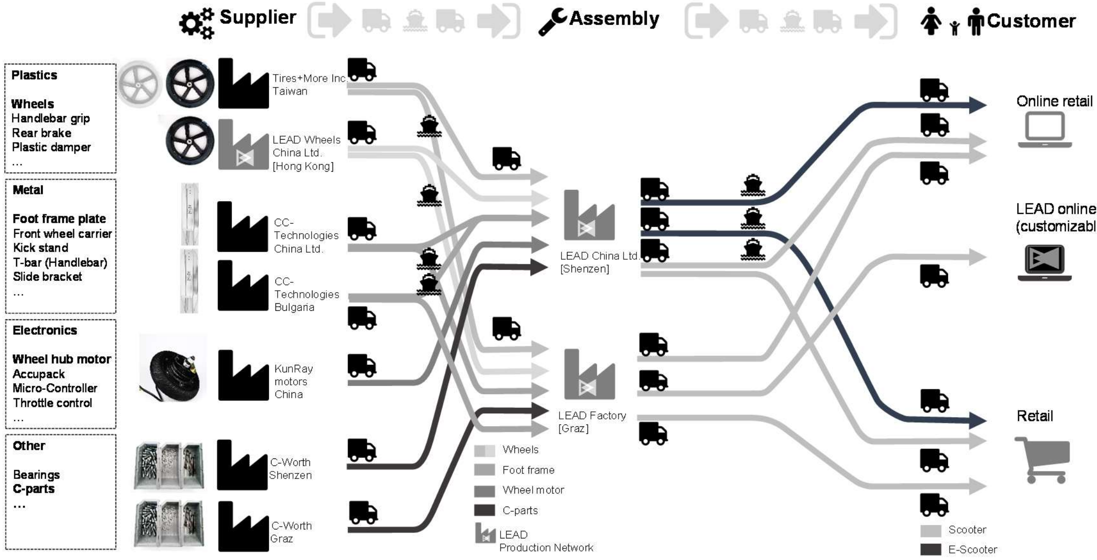


Figure 53: Fictional business environment ‘big picture’ (own illustration – as applied at the LEAD Factory)

The fictional case study provides the framework for further learning factory elements described in the following.

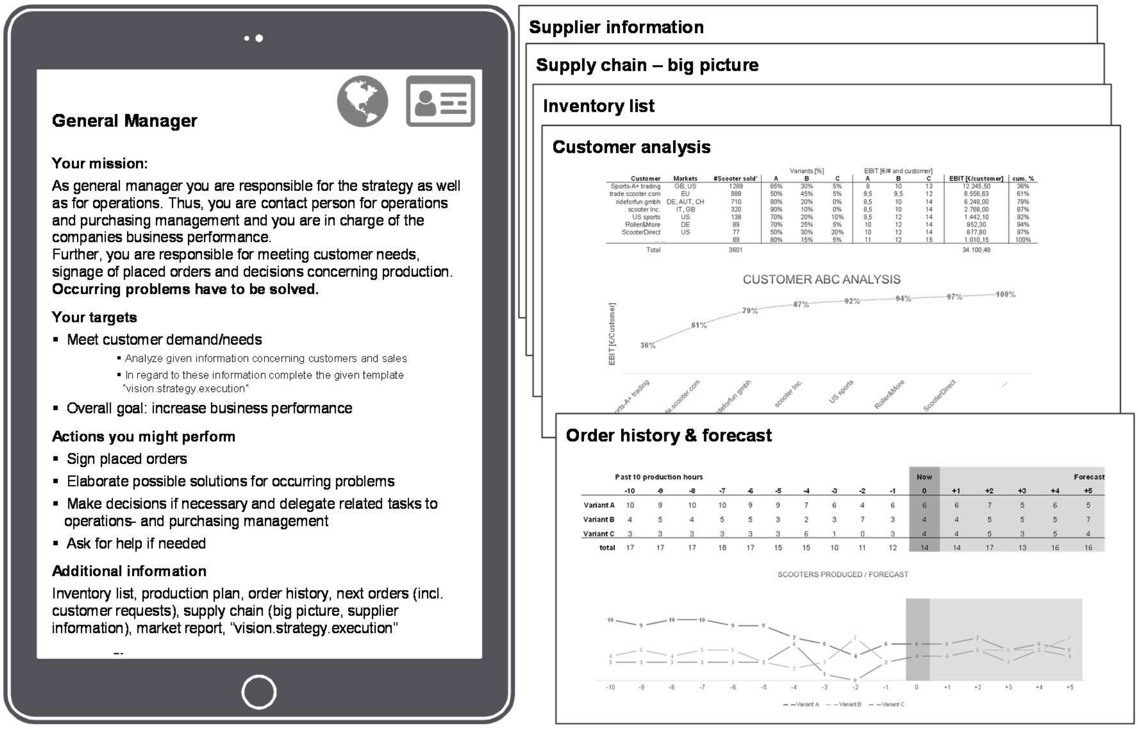
5.5.2 Role-play

Consulted literature (see chapter 2.2) points out that agile operations is a multidimensional approach (e.g. Vázquez-Bustelo et al. 2007, pp. 1305–1306) and that opportunities and disruptions involve any organization level (e.g. Gunasekaran 2001, pp. 27–28). Subsequently, a derived requirement to the learning environment is the abstraction of a real-life company structure in terms of core functions and organizational levels including responsibilities to address issues across the value chain (from suppliers to customers).

The author chose therefore a role-play as an experiential learning method enabling participants to immerse themselves to predefined roles and to take different viewpoints to a learning situation (see section 2.3.3). As previously descripted, *Küsters 2018* used a similar approach to take different views on digitalization in a learning factory course. *Bonz 2009* defined following six phases of a role-play: (1) information; (2) preparation; (3) play experience; (4) discussion; (5) summary of findings; and (6) generalization- and transfer phase (Bonz 2009, 141). In the following the developed role-play for the topic of agile operations is explained according to these phases (see exercise #1 and #10 - section 5.4).

Information about the formal definition of agile operations including the overall goal of optimizing the economic situation and the 'corporate agility system' (see section 2.2.6) are shared with participants. Further, participants are introduced to the learning factory setting (e.g. products produced, operational processes, machinery), general rules, the available roles of the role-play and are then assigned team-wise to the roles of operators, operation managers, purchasing managers and general managers to include at least suppliers, the actual production, strategic decisions and the customer perspective (pre-defined roles are dependent on e.g. the maximum amount of participants). Further, a neutral role of 'observers' record efforts of their peers.

The **preparation** phase includes role descriptions containing e.g. targets and typical actions. Further, each role needs specific additional information regarding their area of responsibility (e.g. purchasing manager - inventory level, supplier structure), see following Figure 54.



General Manager

Your mission:

As general manager you are responsible for the strategy as well as for operations. Thus, you are contact person for operations and purchasing management and you are in charge of the companies business performance.
Further, you are responsible for meeting customer needs, signage of placed orders and decisions concerning production.
Occurring problems have to be solved.

Your targets

- Meet customer demand/needs
  - Analyze given information concerning customers and sales
  - In regard to these information complete the given template "vision.strategy.execution"
- Overall goal: increase business performance

Actions you might perform

- Sign placed orders
- Elaborate possible solutions for occurring problems
- Make decisions if necessary and delegate related tasks to operations- and purchasing management
- Ask for help if needed

Additional information

Inventory list, production plan, order history, next orders (incl. customer requests), supply chain (big picture, supplier information), market report, "vision.strategy.execution"

Supplier information

Supply chain – big picture

Inventory list

Customer analysis

			Variants [%]			EBIT [€/# and customer]				
Customer	**Markets**	**#Scooter sold***	**A**	**B**	**C**	**A**	**B**	**C**	**EBIT [€/customer]**	**cum. %**
Sports-A+ trading	GB, US	1289	65%	30%	5%	9	10	13	12.245,50	36%
trade.scooter.com	EU	889	50%	45%	5%	9,5	9,5	12	8.556,63	61%
rideforfun gmbh	DE, AUT, CH	710	80%	20%	0%	8,5	10	14	6.248,00	79%
scooter Inc.	IT, GB	320	90%	10%	0%	8,5	10	14	2.768,00	87%
US sports	US	138	70%	20%	10%	9,5	12	14	1.442,10	92%
Roller&More	DE	89	70%	25%	5%	10	12	14	952,30	94%
ScooterDirect	US	77	50%	30%	20%	10	12	14	877,80	97%
......		89	80%	15%	5%	11	12	15	1.010,15	100%
Total		3601							34.100,48	

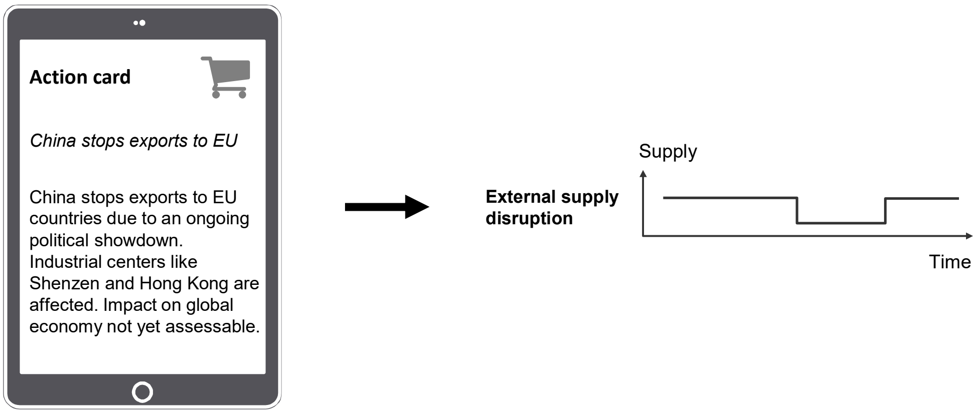
Order history & forecast

	Past 10 production hours									Now					Forecast
	-10	**-9**	**-8**	**-7**	**-6**	**-5**	**-4**	**-3**	**-2**	**-1**	**0**	**+1**	**+2**	**+3**	**+4**	**+5**
Variant A	10	9	10	10	9	9	7	6	4	6	6	6	7	5	6	5
Variant B	4	5	4	5	5	3	2	3	7	3	4	4	5	5	5	7
Variant C	3	3	3	3	3	3	6	1	0	3	4	4	5	3	5	4
total	17	17	17	18	17	15	15	10	11	12	14	14	17	13	16	16

Figure 54: General manager role-card and exemplary additional information (own illustration - as applied at the LEAD Factory)

Throughout the **play experience** phase, participants operate in the learning factory according to their role specific actions and targets. The author of this research suggests that the production facility is separated from the office area where e.g. purchasing management operates in order to increase the difficulty of communication and reaction time. However, as the overall goal is to cope with uncertainty in operations, the trainer has the ability to manipulate operations through the simulation of uncertainties at different business levels (see following Figure 55). As consulted literature concerning trainings for crisis management suggested (see section 2.2.8), the target is that participants experience several uncertainties leading to the typical effects on operations (see section 2.2.6).

Figure 55 shows a so-called ‘action card’ and its intended type of effect on operations. Observers record throughout the role-play the actions of their peers. A group change from observers to active roles and vice-versa in the middle of the exercise proofed to be valuable - see section 6.3.1.



Action card

China stops exports to EU

China stops exports to EU countries due to an ongoing political showdown. Industrial centers like Shenzen and Hong Kong are affected. Impact on global economy not yet assessable.

Figure 55: Exemplary ‘action card’ and intended effect on operations (own illustration - as applied at the LEAD Factory)

Based on the observations of the observers, the debriefing **discussion** focus on occurred events (‘action cards’) and the actual reaction of participants (different roles) to cope with the impact. Using a timeline as basis to structure the discussion proofed to be effective (see section 6.3.1).

Finally, the trainer **summarizes** events, taken actions and outlines potential improvements in relation to the concept of agile operations.

Subsequently, a **generalization** of the experiences takes place in the further course of the training (role-play in exercise #1) or improvements from the non-agile as-is state to the improved agile operations-state is discussed (role-play in exercise #10).

To summarize: The role-play intends to depict a real-life company structure in terms of core functions and organizational levels. This includes at least the representation of responsible roles concerning suppliers (including logistics), production, and customers. Required materials are the role descriptions, additional role-specific information, a standardized observer sheet, and different action cards to simulate uncertainties.

5.5.3 Monitoring system

The monitoring function within the underlying ‘corporate agility system’ of this research study is considered as the interface of the focus company to the external business environment (Heldmann 2018, p. 15). The overall response time of reacting to uncertainties depends especially on early warning signals and their processing (Hernández Morales 2003, p. 49).

Hence, to design an agile operations system, there is the need to understand the importance of early detection, and how to set-up a monitoring system in principle (see section 2.2.6). As outlined in chapter 5.3, a requirement for the learning factory setting is a working monitoring system to track uncertainties within the surrounding fictional business environment described in section 5.5.1. Requirements to the technical system include the ability to simulate uncertainties based on participants’ results of previous exercises (from a trainer perspective) and the possibility for participants to adapt the monitoring system to track 'trigger points' defined by them. The author could not identify a market available product meeting these requirements. Therefore, the author chose to develop a feasible learning factory specific solution.

The underlying technical basis for the developed monitoring system are so called 'RSS[17] Feeds'. *Duffy and Bruns 2006* introduce RSS and its potential usage in education but refer mainly to library services and data exchange in courses. RSS Feeds enable users not to search several single web pages individually to get new information about their content. So-called 'feeds' track updates on a web page using a XML format and users get these updates via a RSS feed reader. (Duffy and Bruns 2006, p. 36)
RSS technology is broadly accepted as an industry standard and RSS feed readers are available for all main operating systems (Chang et al. 2006, p. 287).

Figure 56 shows the interaction principal of web pages, web servers with browsers or RSS feed readers.

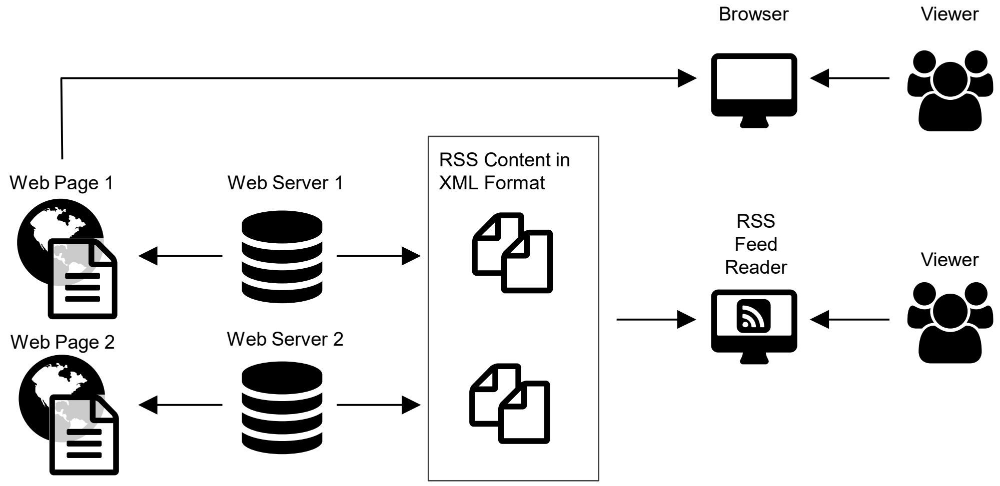


Figure 56: Interaction of web pages and web servers with browser or RSS feed readers (based on Chang et al. 2006, p. 290)

The author chose '*RSSOwl*'[18] as open source RSS feed reader for the application as learning factory monitoring system. Further, the open software program '*XAMPP*' was used to simulate a web server. The basic principle (see Figure 57) of the developed solution consists of several simulated newsfeeds by providing XML-files of 'news' announcing uncertainties within the surrounding business environment on the simulated web server.

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[17] RSS...'Rich Site Summary' or 'Real Simple Syndication' (Duffy and Bruns 2006, p. 36)

[18] For download see: http://www.rssowl.org/ (2021-01-14)

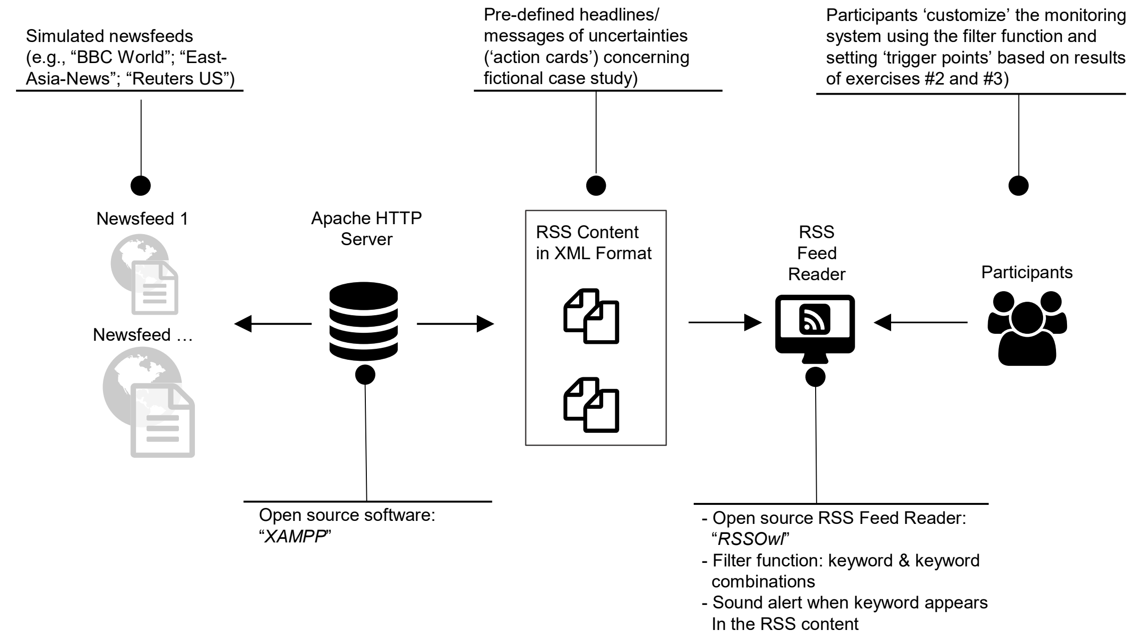
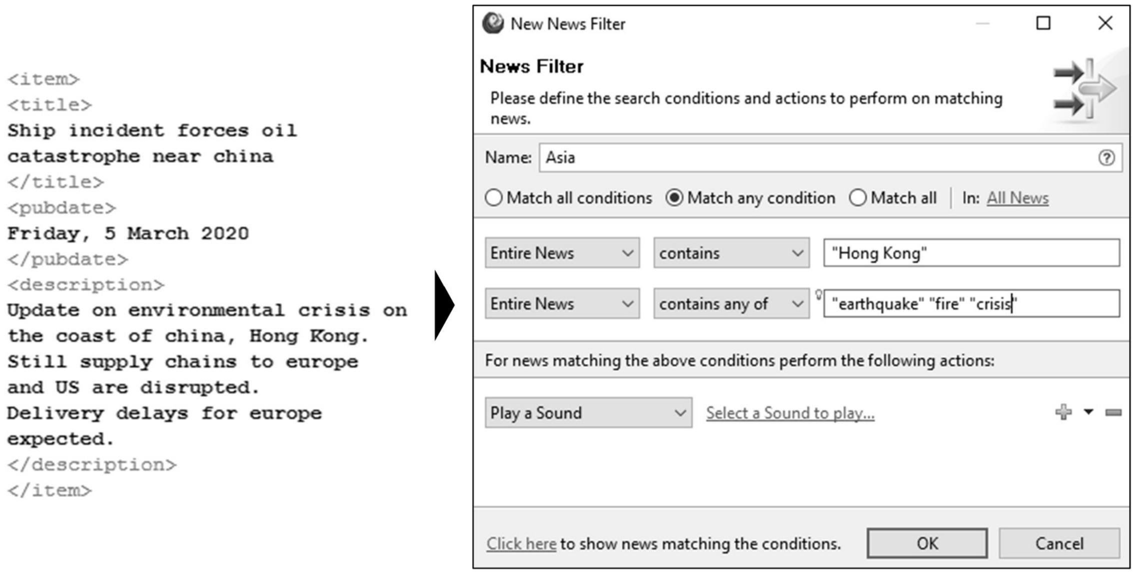


Figure 57: RSS Feed based monitoring system for a learning factory (own illustration)

Participants themselves define trigger points and set-up the monitoring system using specific keywords and keyword combinations within the RSS feed reader. For this, the program used provides a news filter function. The setting of the RSS feed reader installed at several tablet computers (for different participant groups) is preset so that only news are shown when the filter function 'detects' the published (by the trainer) news message. Figure 58 shows on the left an exemplary simulated news message in XML format and the corresponding news filter 'detecting' this event.



```
<item>
<title>
Ship incident forces oil
catastrophe near china
</title>
<pubdate>
Friday, 5 March 2020
</pubdate>
<description>
Update on environmental crisis on
the coast of china, Hong Kong.
Still supply chains to europe
and US are disrupted.
Delivery delays for europe
expected.
</description>
</item>
```

New News Filter

News Filter

Please define the search conditions and actions to perform on matching news.

Name: Asia

○ Match all conditions ● Match any condition ○ Match all In: All News

Entire News | contains | "Hong Kong"

Entire News | contains any of | "earthquake" "fire" "crisis"

For news matching the above conditions perform the following actions:

Play a Sound | Select a Sound to play...

Click here to show news matching the conditions.

Figure 58: Exemplary RSS content (XML Format) and *RSSOwl* filter function (own illustration - as applied at the LEAD Factory)

This non-resource intensive solution of a monitoring system is one building block for the target agile setup of the learning factory. In exercise #1 participants receive an 'action card' with relevant information causing effects on operations intentionally (too) late to react on. In contrast, the monitoring system simulates the possibility to early detect uncertainties throughout the closing exercise #10 where participants experience the implemented agile operations system (see chapter 5.4).

5.5.4 Agile operations business game

The derived requirements (see chapter 5.3) of agile operations on the learning environment are in conflict with current limitations of learning factories (see section 2.4.5). This includes especially resource related, time related and solution related limitations (see chapter 5.3). As previously stated, the author chose a business game approach to overcome these limitations (business games as teaching method are described in more detail in section 2.3.3).

General considerations on business game development

The target of the agile operations business game is to include especially upper-factory levels (e.g. production network) and strategic aspects of the subject matter of agile operations to the learning factory based course. This includes ‘virtual actions’ by participants concerning resource reallocation by implementing agile operations levers causing partly real effects at the physical learning factory and simulated results (see chapter 5.3). Further, the business game intents to support the understanding of key aspects of agile operations like pro-activity, the need for strategic alignment, and the potential impact of agile operations levers (and combinations) on operations. As previously described, the business game runs in parallel to the physical learning factory actions and needs therefore a strong link to the physical processes and products produced (see chapter 5.4).

Kriz and Hense 2008 review several guiding frameworks to develop a business game. The authors further introduce an therefrom derived approach to design a business game to ensure the quality of the final product. The phases of the proposed approach are (1) problem clarification and formulation; (2) system analysis and model construction; (3) design; and (4) development of the business game. The first phase defines the scope of the business game. Within phase two, relevant factors, relationships, variables and parameters are determined and operationalized. The target in this phase is to identify cause effect relationships and to represent those in a logical model. The design phase contains the definition of the actual type of business game (media, participants’ actions, game rules, etc.). Finally, phase four contains the development of a prototypical application including its testing and optimization. (Kriz and Hense 2008, pp. 216–220)

The present research followed the proposed approach by *Kriz and Hense 2008*. Previous sections addressed several aspects of the introduced phases. Chapters 5.3 and 5.4 concerned the general scope of the business game and the principal application within the learning factory setting as conceptualized by *Thiede et al. 2017*. In the further course, this section describes additional aspects of the conducted development phases.

Problem clarification and formulation

The previously stated scope of agile operations, learning targets and requirements of the agile operations business game provide the basic boundary conditions for the model.

First, the underlying definition of agile operations states, that the overall objective is to optimize the economic situation of the respective company (see section 2.2.2). Therefore, the **result of the business game** is expressed as a **financial performance indicator of the company**.

Second, the requirement to closely link the physical learning factory to the business game specifies that the **learning factory is the basis for the company model of the business game**.

Third, in terms of agile operations the overall objective of optimizing the economic situation is achieved through the capability to prepare proactively for uncertainties (see section 2.2.2). Subsequently, **effects of uncertainties on operations are the variables within the business game model.**

Fourth, the agility level of a company defines the operations performance in times of uncertainty (see section 2.2.4). As a result, the target of making agility levers better understandable (including side effects) defines the decision-making of **which agility levers to implement** as the **input to the model by participants**.

Hence, the target is to develop a model of a company, which links operations performance to financial outcomes. A prerequisite of the model is the opportunity to simulate effects of uncertainties on operation (scenarios). The game input from participants is defined as the selection of agile operations levers counteracting those effects. Despite the natural objective of creating a model as realistic as possible trade-offs are necessary or as *Gentry 1990* puts it: “*[...] it is how well the simulation meets its stated purposes, not its apparent realism, that is important.*“ (Gentry 1990, p. 110)

System analysis and model construction

The model describes the operating procedure (formulated in equations) processing the decision input (by participants) and combines it with the simulated corporate conditions to calculate the outcomes (Gentry 1990, pp. 97–99).

Cachon and Terwiesch 2020 state that a company achieves economic value by increasing its return on invested capital (ROIC). The authors propose a so-called Key-Performance-Indicator (KPI) tree to link operational performance with the financial ROIC KPI. (Cachon and Terwiesch 2020, pp. 109–110)
The company Du Pont first used the concept of ROIC at the beginning of the 20th century using such a KPI-tree (or ‘DuPont Scheme’) to show the cause-effect relationships of factors influencing the return on investment (Chandler 1977, p. 44). This accounting tool enabled modern management to sharpen its procedures for the administration of e.g. production processes, distribution, operations improvements or resource reallocation (Chandler 1977, pp. 447–448).

Thus, the KPI of ROIC is a suitable financial performance indicator to show the impact of operations on corporate economic value creation. However, the author of this thesis chose to create a fictional KPI for the business game representing the profit of a company in relation to the capital invested in agile operations measures (cost of agile operations levers) to simplify the complexity in order to enhance the learning experience. The fictional KPI is referred to as 'ROIC_A'.

Further, as *Koller et al.* state, a KPI-tree "*[…] is a systematic method for analytically and visually linking a business's unique value drivers to financial metrics.*" (Koller et al. 2015, p. 586). Therefore, the author chose to use a basic KPI-tree to describe a company's mechanics. The term 'company' in this context refers to the learning factory surrounding business structure. Figure 59 shows the basic KPI-tree used for the business game applied at the LEAD Factory (see chapter 6).

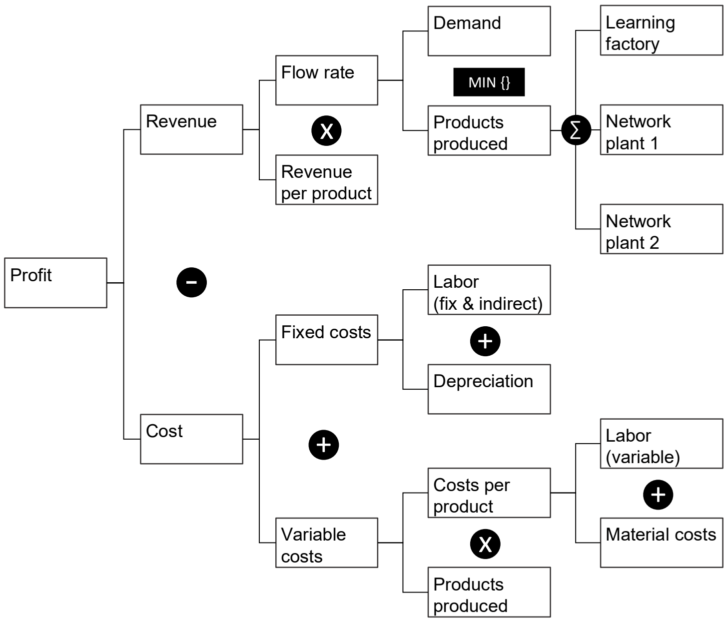


Figure 59: KPI-tree of the learning factory 'company' (adapted from Cachon and Terwiesch 2020, p. 115; Bernstein and Wild op. 1998, p. 477)

As Figure 59 shows, the revenue stream contains the so-called 'flow rate' describing the potential maximal sales limited by either the demand or the production capabilities of the company. The products produced are dependent on the production capacities of the production sites. As shown, one production site within the business game is the physical learning factory, which serves as direct link to the virtual game. Additional production sites are fictional internal or external (e.g. contract manufacturer) network organizations. The cost stream consist of fixed and variable costs depending on the produced products. The basis to derive a suitable cost structure to complete the KPI-tree are the physical learning factory processes (e.g. number of employees) and the product processed (e.g. revenue per product).

Besides the simulated company mechanics, the business game model processes the participants' input. As previously stated, the input by participants is defined as the implementation of different agile operations levers to adjust the agility level of the company. The author suggests to include exemplary agile operations levers from each high-level category (work organization, production assets, purchasing, logistic, production network, product design) as introduced in section 2.2.6 to show the potential of the concept of agile operations. Concerning the application of the developed business game at the LEAD Factory (see chapter 6), the author chose to implement selected levers proposed by *Pointner 2017* (see Table 3). Similar to *Schurig 2016*, the author chose to enable the implementation of agility levers in three implementation stages (most agile > moderate agile > least agile).

The bachelor thesis of *Saiko 2019* supervised by the author of this thesis contributed to elaborate the agile operations levers used in the agile operations business game developed in the course of this research study.

Table 42 shows exemplarily one of the included agile operations lever (and implementation stages) in the business game as applied at the LEAD Factory.

Table 42: Implemented agile operations lever 'fast reaction in logistics' (based on Pointner 2017 pp. 204-224; Saiko 2019, p. 26)

Most agile	**Moderate agile**	**Least agile**
- Alternative solutions for transports from Chinese, Taiwanese and European suppliers (inbound) and to our customers (outbound) are evaluated - Framework agreements are prepared - Changes due to disruptions are possible at short notice	- Alternative solutions for European suppliers (inbound) and transports to our customers (outbound) are evaluated - Changes are partially possible at short notice	- Standard means of transport are available - No further options are evaluated

Cause-effect relationships of levers (and lever combinations) and the company model must be defined. *Kriz and Hense 2008* proposes to apply the method of 'network thinking and acting' as described by e.g. *Vester 2007*. This research study used the instrument 'Design Structure Matrix' proposed by *Eppinger and Browning 2012* to identify interrelations of chosen levers.

Figure 60 shows exemplarily the impact of agile operations levers on the company model as applied at the LEAD Factory (e.g. investing in input factor monitoring reduces material costs).

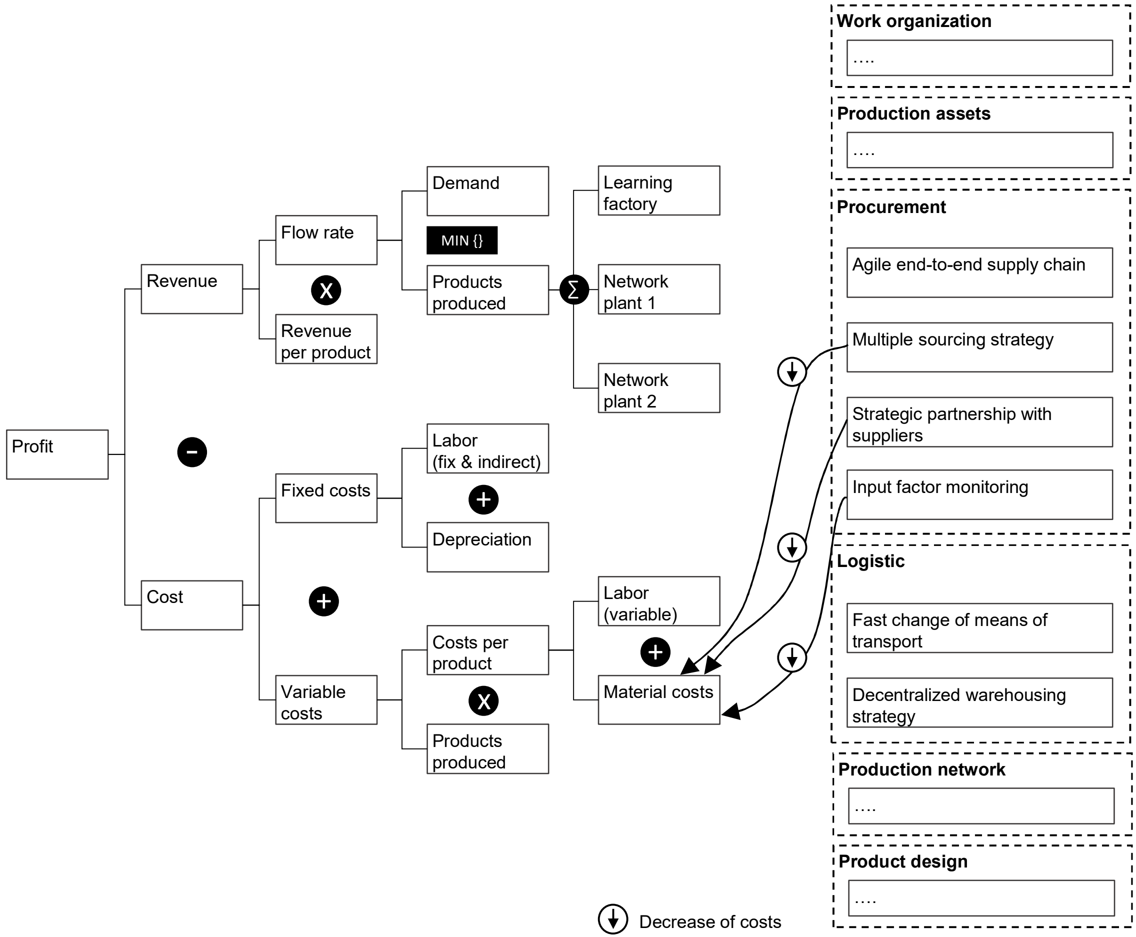


Figure 60: Exemplary effect of agile operations levers on the company model (own illustration - as applied at the LEAD Factory)

However, the shown impact in Figure 60 refers to the 'standard configuration' of the company without disruptions caused by uncertainties. Therefore, variables to include (external) change drivers need to be defined. These variables simulate the effects of different uncertainties on operations (see section 2.2.7) within the derived company model. To depict different uncertainties causing varying impacts on operations, the author recommends the development of at least KPI-tree configurations for the following four scenarios: (1) demand upswing; (2) demand downswing; (3) logistic disruption; and (4) supply chain disruption. Further scenarios might include product mix changes, technological disruptions or unpredictable raw material price developments. The actual variable(s) to simulate the scenarios differ. Demand related impact is linked to the 'demand' element of the KPI-tree (see Figure 61). Whereas disruptions to logistics and suppliers cause internal production downtime linked to the 'products produced' element of the KPI-tree. Combinations of several variables for one scenario are possible but increased complexity of the model might negatively influence the learning process. Different levers (and lever combinations) in place counteract the actual impact on the model of each scenarios. Hence, levers influencing a certain element of the KPI-tree in scenario 1 might cause different effects in scenario 2. Further, dependencies of levers need to be considered as certain combinations might increase or decrease the impact on operations (see section 2.2.6). To balance the impact of levers and their combination the author used the method of 'pairwise comparison'.

Figure 61 shows an example of a scenario simulating a logistic disruption as applied at the LEAD Factory. The variable 'products produced' is set to 70% of its baseline value due to the logistic disruption. The demand however, does not change. Implemented levers (and lever combinations) might increase the preset value of 70% to simulate the impact of agile operations. To give an example, the lever 'agile end-to-end supply chain' in combination with the lever 'fast change of means of transport' decreases the impact of the logistic disruption more than the sum of the individual lever applications. For more details concerning the lever and lever combinations impact on the company model see Appendix G.

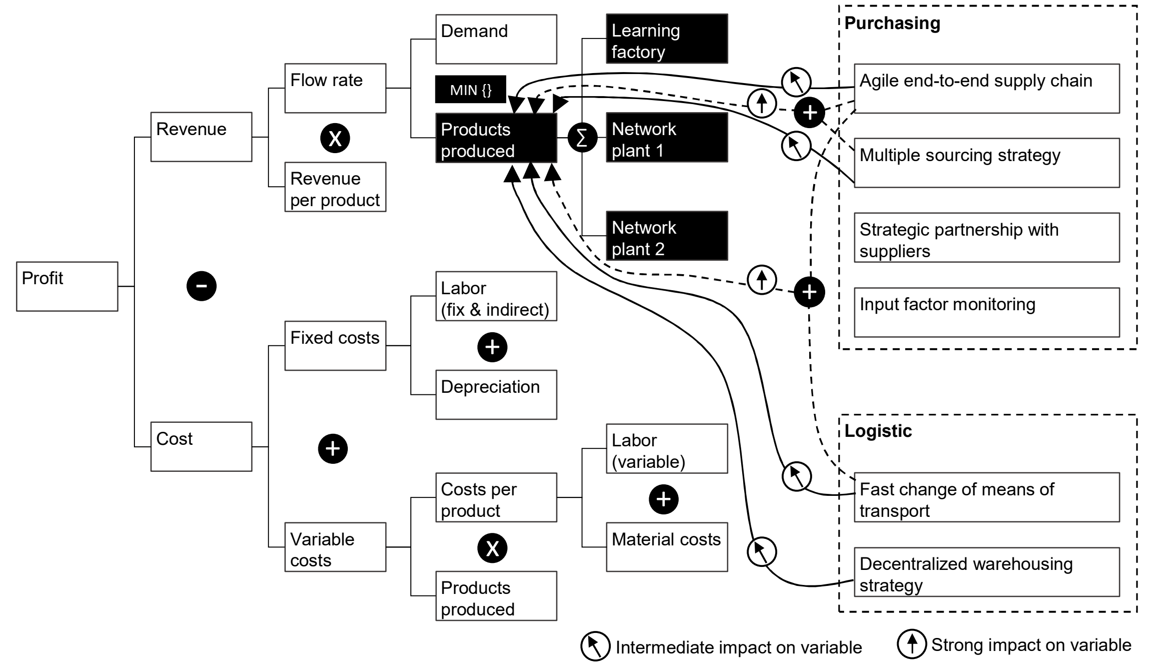


Figure 61: Impact (exemplary) of agile operations levers on the variable 'products produced' simulating a logistic disruption (own illustration - as applied at the LEAD Factory)

Design

The business game consists of an information phase, a decision phase, the parallel actual hands-on learning activity in the learning factory and a final evaluation phase. The information phase provides participants with additional key information concerning the business environment and the learning factory company (similar to the role-play – see section 5.5.2). Based on these information and the elaborated elements of previous exercises participants decide which agile operations levers they want to implement. However, as in reality investment possibilities are limited each lever implementation stage costs a different amount of a limited capital.

After the decision phase, the hands-on exercise starts in the learning factory (exercise #10 - see chapter 5.4) where participants' experience their designed agile operations system (monitoring system implemented, elaborated hierarchical structures applied, etc.). Virtual chosen agile operations levers cause a direct physical impact (when applicable). Further, to closely link both activities any uncertainties that arise (defined by the trainer) are aligned in-between the hands-on exercise and the business game. Finally, the evaluation phase combines in a detailed debriefing discussion experiences from real and simulated results.

Figure 62 provides an overview of the combination of business game and hands-on activities in the learning factory.

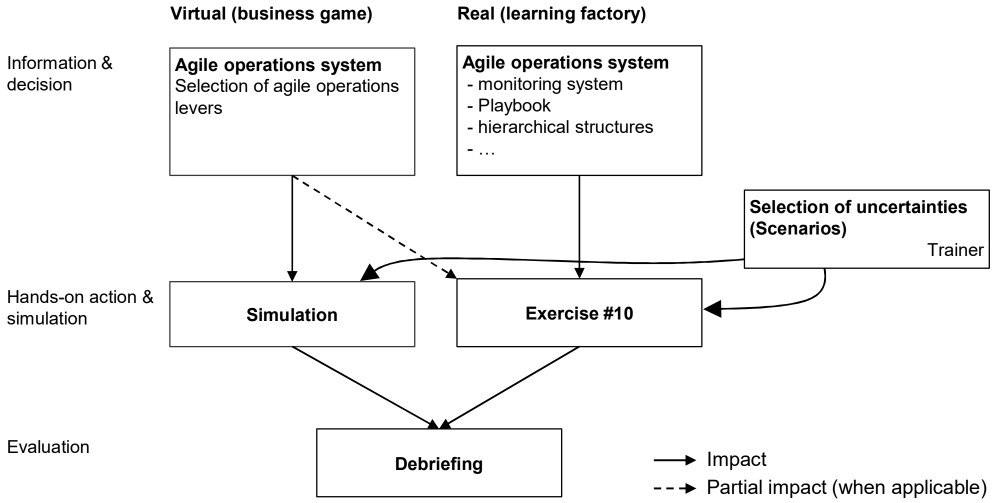


Figure 62: Combination of the business game and the learning factory based exercise #10 (own illustration)

While physical experiences are evaluated based on the introduced performance measurement scorecard approach (see section 5.4), the business game provides results of the impact of agile operations in terms of financial and operational performance. Operational results show the match of demand versus production capacity over time. Financial performance is correspondingly shown as the previous described $ROIC_A$. These results are presented to the participants in the form of a timeline to structure the debriefing session.

Figure 63 shows exemplary the final results of the developed business game for the LEAD Factory.

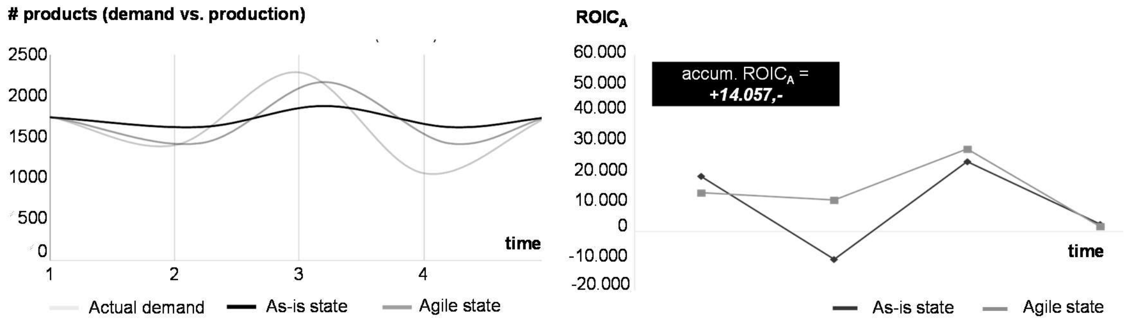


Figure 63: Results (exemplary) of the business game (own illustration)

Development

The author of this thesis used a spreadsheet model (‘*Microsoft Excel*’) for the prototypical realization of the business game. As can be seen, the number of scenarios, the levers (including the different implementation stages), interdependencies of levers and the complexity of the company mechanics itself create complexity. Therefore, consulted literature points out that iterative testing and (re-) modelling is necessary to ensure a satisfactory performance of the business game model (Kriz and Hense 2008, p. 219). Literature recommends continuous validation of the model directly throughout the building phase of the model (see e.g. Law and Kelton 2000, p. 266). Subsequently, the author tested the company mechanics (standard configuration) before implementing scenarios and levers. The impact of variables on the standard configuration as well as in the further course the impact of agile operations levers (and combinations) on each scenario were iteratively tested and adapted individually to obtain a balanced and reasonable model behavior. Examples for adaptions to the model are the extent of the variability of the input factors (impact of levers) or the severity of the impact on operations by simulated uncertainties (variables). However, as previously stated, the focus is on achieving the learning objectives rather than on pure realism.

To validate the developed prototype several simulations by the author and with peers (familiar and non-familiar with the subject matter of agile operations) were conducted. As *Feinstein and Cannon 2002* propose, especially aspects of internal validity (to which extent does the model simulate relevant phenomes realistically?) and external validity (are necessary competences for the reality addressed?) were discussed in these validation runs (Feinstein and Cannon 2002, pp. 434–437). Internal validity addresses e.g. the question if participants are able to identify assumed effects of implemented levers for specific scenarios in the business game results. Whereas external validity relates to the connection of predefined learning objectives and the business game. The validation runs provided valuable insights and obtained feedback contributed to the final version of the agile operations business game for the LEAD Factory.

Further, the author supervised the bachelor thesis of *Rinnhofer 2021* with the aim of programming a JavaScript-based application of the developed Excel-based prototype.

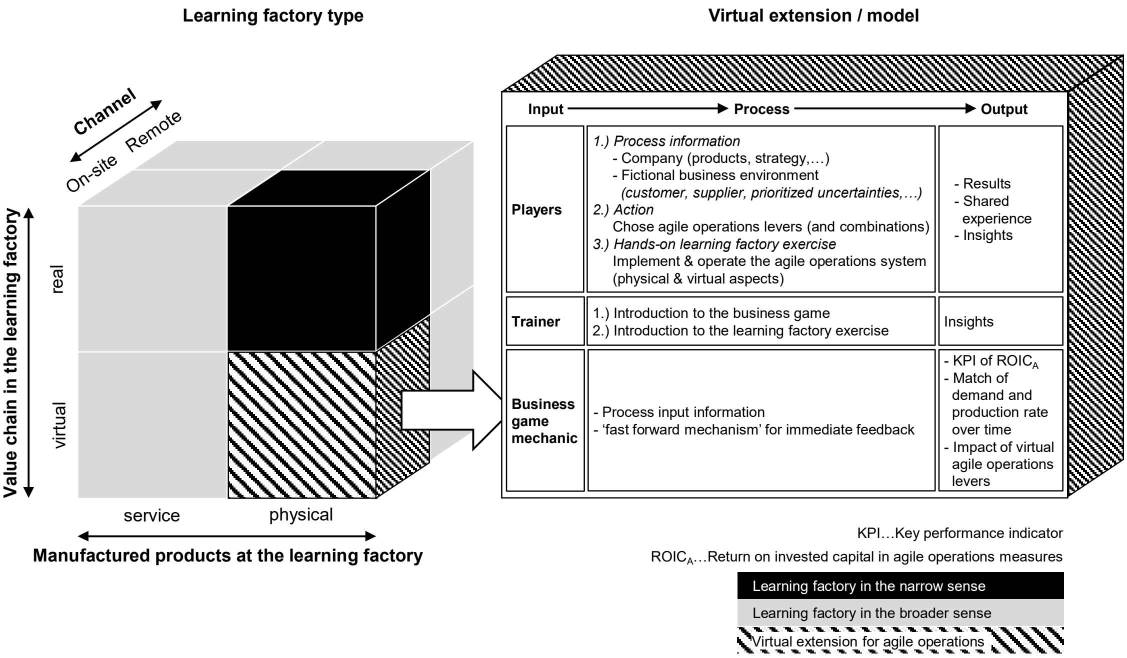
5.6 Summary: Conception of the teaching concept

The author of this research developed a training course to ‘design an agile operations system’ based on the guiding framework proposed by *Tisch 2018*. The underlying competence was formulated as:

Participants of the agile operations training are able to design an agile operations system to cope with uncertainty in operations.

A literature study was conducted to breakdown this main competence in its consisting elements (sub-competences, observable actions and knowledge elements). Based on the chosen underlying agile operations framework, the four training modules of ‘uncertainty’, ‘monitoring’, ‘strategic alignment’ and ‘governance’ were derived. Further, the consisting elements of the main competence served to derive requirements for the learning environment on all involved factory levels (from production network level to the shopfloor level), the necessary surrounding business environment and the products processed.

This research outlined sequences of single exercises (micro level) based on the formulated (sub-) competences, derived requirements, and initial solution strategies. The chosen solution approach combines different experiential teaching methods including a case study about the fictional business environment, a role-play, and an agile operations business game. The developed business game can be characterized as computer supported, interactive, trainer led model of a corporate system played by user groups in parallel (according to Blötz 2008b, p. 54). The resulting learning factory state (‘agile state’) combines physical and virtual elements and can therefore be considered as ‘hybrid learning factory’ (see section 2.4). Figure 64 shows the ‘input - process - output’ model of the developed virtual extensions (fictional business environment and business game) based on *Lewis and Maylor 2007* (see section 2.3.3). Further, the author developed a monitoring system based on RSS Feeds.



Input	Process	Output
Players	1.) *Process information* - Company (products, strategy,…) - Fictional business environment *(customer, supplier, prioritized uncertainties,…)* 2.) *Action* Chose agile operations levers (and combinations) 3.) *Hands-on learning factory exercise* Implement & operate the agile operations system (physical & virtual aspects)	- Results - Shared experience - Insights
Trainer	1.) Introduction to the business game 2.) Introduction to the learning factory exercise	Insights
Business game mechanic	- Process input information - ‘fast forward mechanism’ for immediate feedback	- KPI of $ROIC_A$ - Match of demand and production rate over time - Impact of virtual agile operations levers

Figure 64: Developed virtual extension using the agile operations business game (own illustration)

Table 43 lists main contributions of these elements to the developed agile operations training course and lists the exercises were these extensions are applied specifically.

Table 43: Contributions of agile operations specific learning factory elements

Element	Main contribution to the training course	Exercise
Case study: fictional business environment	- Mapping of the surrounding business environment (including potential uncertainties) - Inclusion of suppliers, production network (internal & external) and customer perspective - Basis for the training course (role-play, monitoring system, business game)	#1; #2; #3; #4; #6; #7; #8; #9; #10
Role-play	- Enabling different viewpoints on agile operations (corporate functions) - Abstracted depiction of corporate hierarchies - Possibility for participants to adapt responsibilities and processes (e.g. playbook) concerning agile operations	#1; #9; #10
Monitoring system	- Basis for “early detect and fast react” - Participants can program it individually based on their findings	#4; #10
Business game	- Feasible solution to overcome barriers concerning time-, resource- and solution-related limitations of learning factories - Linking operational performance with financial KPIs - Possibility to simulate different effects on operations caused by uncertainties - Enabling to experience the impact of agile operations levers	#8; #10

CHAPTER 6
Results

This chapter presents the gathered data from conducted trainings and discusses derived learnings. The training actions are set according to the chosen research design of 'action research'.

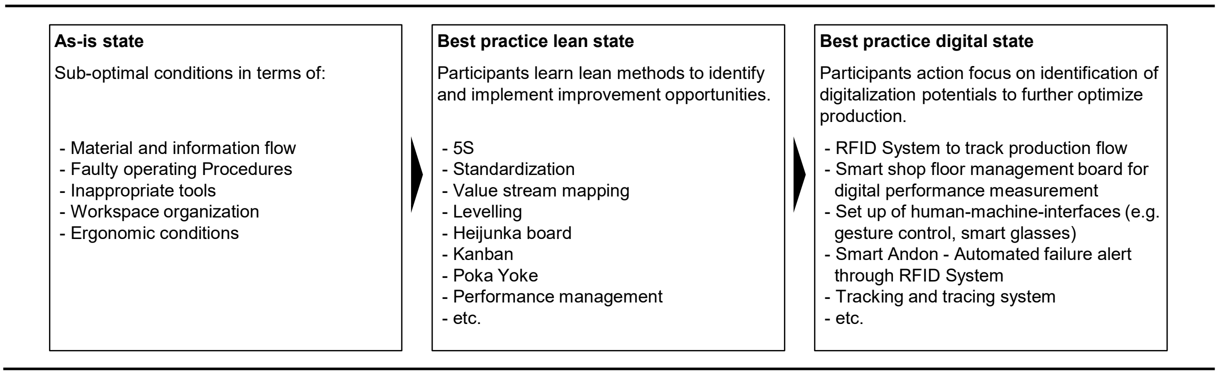
First, this chapter introduces the LEAD Factory and pre-conditions related to the application of the developed training actions. Second, it introduces and discusses the results of conducted trainings within action research cycle 1. Subsequently derived further developments are described and applied in action research cycle 2. Further, this chapter introduces and analyzes obtained data of action research cycle 2 trainings and their discussion. Finally, the results of the conducted quasi-experiment comparing the learning factory treatment with a frontal lecture treatment as teaching method are presented.

6.1 The LEAD Factory

The developed teaching approach for agile operations was applied at the learning factory at the Institute of Innovation and Industrial Management (IIM) at Graz University of Technology. The author of this research published several articles with brief descriptions of the LEAD Factory (e.g. *Karre et al., 2017*; *Karre et al., 2018*). The following section describes relevant aspects of the LEAD Factory for the present work based on previous publications.

The acronym 'LEAD' refers to the main topics (**L**ean, **E**nergy-efficient, **A**gile, **D**igital) addressed at the learning factory. For more details see e.g. *Karre et al. 2018*. The LEAD Factory is in operation since 2014 focusing initially on the topics of industrial engineering, logistics and energy-efficiency (Micheu and Kleindienst 2014, p. 405). The further development of the LEAD Factory was continuously driven by research projects at the IIM. The focus on digitalization was first outlined by *Karre et al. 2017* and is still being developed and improved today (see e.g. Hulla et al. 2019b; Auberger et al. 2019; *Eder et al. 2020*). The content and teaching approach concerning the subject matter of **agile operations** is elaborated in the course of the present research study.

The product produced at the LEAD Factory is a market available scooter in specific TU Graz design. The learning factory infrastructure focuses mostly on assembly tasks. However, one of the 60 parts of the scooter is produced directly at the learning factory with a 3D-printer. Further, a CNC-mill simulates customization aspects. In addition, three different variants of the product are produced (e.g. different color of wheels). The didactical concepts regarding the topics of lean, energy-efficiency and digitalization are build upon three maturity states. An initial sub-optimal current state, a best-practice lean state and a digital state (see Figure 65). Participants iterate the learning factory setup towards the aimed maturity stages elaborating and implementing possible solutions in hands-on exercises and short intertwined theory sessions. Predefined KPIs (e.g. throughput time, number of defects, energy consumption) provide direct feedback concerning implemented solutions. The best-practice lean state as well as the digital state consist of five assembly workstations and one logistic workplace. The maximum group size of participants is limited to 16 persons.



As-is state

Sub-optimal conditions in terms of:

- Material and information flow
- Faulty operating Procedures
- Inappropriate tools
- Workspace organization
- Ergonomic conditions

Best practice lean state

Participants learn lean methods to identify and implement improvement opportunities.

- 5S
- Standardization
- Value stream mapping
- Levelling
- Heijunka board
- Kanban
- Poka Yoke
- Performance management
- etc.

Best practice digital state

Participants action focus on identification of digitalization potentials to further optimize production.

- RFID System to track production flow
- Smart shop floor management board for digital performance measurement
- Set up of human-machine-interfaces (e.g. gesture control, smart glasses)
- Smart Andon - Automated failure alert through RFID System
- Tracking and tracing system
- etc.

Figure 65: Initial maturity states of the LEAD Factory including exemplary key-elements
(own illustration)

In order to gain further insights into the LEAD Factory operating model, the morphology of learning factories proposed by *Abele et al. 2018* shows the pre-study setup of the LEAD Factory (see Appendix F).

To justify the suitability of the LEAD Factory as case for the present research study sampling criteria proposed by *Miles and Hubermann 2008* were considered. To the author the LEAD Factory provides **relevance** (relevant to answer research questions), **appearance** (will the intended effects occur within the case?), **generalizability** (generalizability of findings – e.g. to other learning factories), **believability** (are gathered data samplings believable?), **feasibility** (are aspects as time or access to participants achievable?) and does not violence aspects of **ethics** (e.g. relationship with participants). (Miles and Huberman 2008, p. 34)

As all requirements are met, the integration of the subject matter of agile operations is suitable concerning this research study and enables the extension of an 'agile state' to the LEAD Factory concept.

6.2 Pre-conditions of the application at the LEAD Factory

Due to the given infrastructure (workplaces, products, etc.) certain restrictions concerning elements of the developed training are necessary. The overall number of conducted trainings and included participants of this research study for data gathering were limited due to the research study period and accessibility related limitations.

The learning factory infrastructure at the LEAD Factory itself fulfilled the defined baseline conditions (see Appendix E and F) for the developed teaching approach. This includes aspects such as products (incl. variants and complexity) as well as the defined requirements concerning lean production. However, the processes focus especially on assembly tasks with two exceptions of a 3D-printer and a CNC-mill for customization of the products. Further, there is no focus on process automation. The author considers especially the lack of more real-life production machines as a limitation. No preliminary work regarding the presented extensions of the case study, the role-play, the monitoring system or the business game were available. However, concerning 'digitalization' the LEAD Factory exceeded defined baseline requirements. Especially as outlined in section 2.2.6, digitalization elements can be seen as enabler for agile operations (e.g. technologies enabling faster reaction in production). The author chose to use the digital state of the LEAD Factory as initial non-agile state. The decision was based on the fact that then implemented digital tools already support a better reaction to disruption on shopfloor level (e.g. multiple takt-times). This should prohibit that potential countermeasures to uncertainties brought up by participants focus too much on pure digital solutions. Following considerations to enable comparability among conducted trainings with available resources were included.

First, participants are students enrolled in technical engineering master programs at Graz University of Technology[19]. The majority of participants of the learning factory courses (n=50) were either enrolled in study programs related to mechanical engineering (or mechanical engineering and business economics) (n=25) or enrolled in computer science and software engineering related studies (n=16). Further study programs of participants were chemical and pharmaceutical engineering, biodmedical engineering, civil engineering and business administration.

Second, in order to reach a common basis in terms of existing production related knowledge, all participants attended prior to the agile operations training course a 2-day lean training at the LEAD Factory. Further, as outlined in section 4.4, to evaluate participant's pre-knowledge and to set a baseline for the assessment of training results, a pre-test was developed and applied. This enabled a basic indication concerning comparability of prior knowledge across different participants and participant groups.

All participants were already familiar with the product and processes of the LEAD Factory due to the prior 2-day lean training. However, the author recommends in general to train core lean elements in advance to the agile operations training course. This enables participants to become familiar with processes and products of the learning factory and serves further as recapitulation of necessary basic knowledge.

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[19] Two students (training action 4, 03-04 March 2021) were still enrolled in bachelor studies

6.3 Action research cycle 1

As outlined in chapter 4, the action research cycle 1 provides the opportunity to learn. This research cycle contains two separate conducted trainings. The first training action 'part A: sensing' included the modules of 'uncertainty' and 'monitoring'. The second training action 'part B: responding' addresses the sub-competences of the modules 'strategic alignment' and 'governance'. Following the presentation of gained results, this section closes with an interim conclusion discussing the results and outlining the need for action. As previously described, action research cycle 1 activities and exercises are not fully corresponding with introduced course elements in chapter 5 as elements were further developed throughout this research study.

6.3.1 Part A: Sensing

The training action was conducted on March 7th 2019. This training action addressed the sub-competences related to the module 'uncertainty' and 'monitoring. Hence, participants did experience exercises #1 to #4 (see Table 39). The detailed schedule can be found in Appendix H. Table 44 provides general training course information.

Table 44: Training action 1: part A – general information

Content	Date	Trainer	Data gathered	Participants
Module 1: **'uncertainty'** - SC1: identify and structure - SC2: analyze and prioritize Module 2: **'monitoring'** - SC3: analyze, define and select - SC4: structure and generate	March 7th 2019	Author	- Pre-post knowledge test - Peer observation - Evaluation of intermediate training results - Questionnaire	Investigative group 1, n =14 - Computer science and software engineering (n=7) - Mechanical engineering (n=4) - Chemical and pharmaceutical engineering (n=1) - Biomedical engineering (n=1) - Not named (n=1)

SC…Sub-competence; n…Number of participants

Despite the prior 2-day lean course and the knowledge of participants, results of the pre-knowledge test show that there was no substantial knowlegde regarding the test questions. The post-test results regarding to sub-competence 1 (SC) (identify and structure uncertainties) showed a positive impact of the training. The impact of the training course on the related question 1 shows an absolute increase of 63 % in average of correct answers between pre and post-test results. Learning achievements regarding question 2 addressing SC 2 (analyze and prioritize effects of uncertainties on operations) show an absolute increase of 58,9%. The question addressing sub-competences of the module 'monitoring' shows the least learning effect with an absolute increase of 30%.

Table 45: Pre-post knowledge test results (part A)

	Question 1		Question 2		Question 3	
	Max. 6 points (=100%)		Max. 4 points (=100%)		Max. 5 points (=100%)	
	Pre	Post	Pre	Post	Pre	Post
Average points	0.71	4.50	0.14	2.50	0.07	1.57
Standard deviation	1.67	2.13	0.52	1.88	0.26	1.40
Average result [%]	11.9	75.0	3.6	62.5	1.4	31.4

Topic question 1: origin areas of uncertainty (sub-competence 1: identify & structure)
Topic question 2: impact of uncertainties on operations (sub-competence 2: analyze & prioritize)
Topic question 3: functions and benefits of a monitoring system (sub-competence 3: analyze, define & select)

Peer observation of intermediate training results aimed to capture participants' reaction, to identify how participants cope with 'real situations' and to gather information concerning the effectiveness of applied teaching methods. Table 46 summarizes the key-statements from the obtained peer observation sheet (see Appendix B). In correlation with the results of the pre-post knowledge tests the statements show a need for action with regard to monitoring.

Table 46: Key-statements of peer observation protocol (part: A)

Participants reaction	Learning environment, teaching methods and exercises
- Students kept being engaged (not too easy not too hard to come up with solutions) - Motivation was high - Participants recognize cause-effect relations of uncertainties and operations - Student products demonstrate satisfaction concerning learning objectives	- Experiments/exercises are important supplements to the course (match of theory and exercises) - Experiments/exercises develop intended learning objectives - Further exercise regarding 'monitoring' needed - Lack of clear instruction in the LEAD Factory for exercise #1

The author (trainer) observed the training course with similar targets as the peer observation. Furthermore, the author has recorded deviations from the sequence originally planned by himself. There are no inconsistencies in the independent records of the peer observer and the author. Table 47 shows key-aspects of the subjective author observation and the changes occurred in comparison to the planned conduction of the training.

Table 47: Evaluation of intermediate results – observations by the author (part A)

Exercise	Duration (planned)	Deviation from expectation	Subjective assessment of author
Exercise #1	60 min.	- Throughout the exercise, the roles were exchanged (not planned) - In total seven action cards used (original planned: three)	- Target of (suboptimal) 'non-agile state' exploration achieved - Exercise discussion based on the 'timeline' on the board is good and can be used throughout the course several times as reminder of the 'non-agile state' - Role of participants as 'observer' necessary for following debriefing discussion
Exercise #2	45 min.	-	Methods (PESTEL, Porter's 5 Forces, Ishikawa diagram) for identifying uncertainty at different areas of origin work well
Exercise #3	30 min.	Deviation of +20 minutes from original planned time	Results of the probability impact matrix are suitable for subsequent exercise.
Exercise #4	60 min.	Technical issue with monitoring system (5 min. delay)	- Implemented monitoring system builds upon previous exercises, and is suitable for subsequent exercises - Further exercise concerning dependability of monitoring system with 'agile operations levers' and 'governance' is needed

Finally, participants were asked directly after the training action to answer a structured questionnaire. The intention was to capture participants' reaction to the training course from their point of view. The questionnaire evaluation shows satisfactory results with regard to the balance between learning objectives and applied teaching methods, subjective perception of the participants on the topic of agile production itself, the positive influence of experiences and practical examples on the learning process and the form of collaboration throughout the course. However, the time for reflection was perceived lower than all other items.

Table 48 shows the average answers (5-point Likert scale, from strongly disagree to strongly agree) and the standard deviations concerning each item (see Appendix B for full questionnaire).

Table 48: Questionnaire results (part A)

Factor	Item(s)	Objective of inquiry	Average points	Standard deviation
Constructive alignment	1,	Alignment between training course objectives, teaching methods and used media (Entwistle et al. 2003, p. 91)	**4.21**	**0.41**
	2,		**4.36**	**0.61**
	3,		**4.36**	**0.72**
	4		**4.79**	**0.41**
Stimulating tasks	5	Students perception of the importance of given problems in learning situations (Borglund et al. 2016, p. 10)	**4.71**	**0.45**
Exploration and own experience	6,	Contribution of participants experiences made within the training course to the overall learning process (Borglund et al. 2016, p. 10)	**4.14**	**0.74**
	7		**4.07**	**0.80**
Challenge	8	Perception of challenge of learning situations – challenging and stimulating but not overwhelming to students (Borglund et al. 2016, p. 10)	**4.29**	**0.70**
Understanding of the subject	9,	Deep understanding enforced through e.g. (1) relation of the course to prior knowledge; (2) link of subject matter to practical examples and (3) the support of learning activities to enhance key-concept understanding (Borglund et al. 2016, p. 11)	**4.43**	**0.49**
	10,		**4.36**	**0,48**
	11		**4.43**	**0.62**
Adequate prior knowledge	12	Have participants the necessary knowledge base or is this knowledge sufficiently addressed throughout the training course (Borglund et al. 2016, p. 12)	**4.29**	**0.80**
Time for reflection	13	Reflection opportunities of participants on their learnings throughout the course (Borglund et al. 2016, p. 12)	**3.86**	**0.83**
Collaboration	14	Opportunities for participants to collaborate (Borglund et al. 2016, p. 12)	**4.64**	**0.48**
Support	15	Opportunity for participants to get support in their learning from trainer/peer participants (Borglund et al. 2016, p. 12)	**4.50**	**0.63**

Number of participants = 14; answers from 1 (strongly disagree) to 5 (strongly agree)

Further, the questionnaire contained open-ended questions to gather further comments on participants' perception of training course elements and optimization potentials (see Table 49).

Table 49: Participants' comments on open-ended questions (part A)

General comments: **'best aspects of the course'**	- Experiences due to the combination of lecture and hands-on activities - Direct implementation - Group discussions
General comments: **'suggestions to improve'**	- More detailed exercise instructions - Provide more practical examples - Provide more time to reflect
Exercise #1	- Named as "best aspect" of training (3x) - More time to reflect during and after the exercise necessary - Time to react on uncertainties to short
Exercise #2	Handouts are lacking and existing handouts should be aligned with subsequent exercise material
Exercise #3	No comments
Exercise #4	- Task 01 (fault tree analysis) needs more detailed instructions (concrete example) - Technical issues should be resolved (RSS-Feed)

6.3.2 Part B: 'Responding'

The training action was conducted on December 13th 2019. Appendix H provides the detailed course schedule. Trainer and data gathering methods were the same as in training action 1. However, participants' study program background was different. A clear majority was enrolled in mechanical engineering (or mechanical engineering and business administration) related master programs. This training action aimed solely to test the modules 3 and 4. Therefore, the content of the first two modules was taught in theoretical form and actual results of respective exercises were handed over to the participants and discussed. This detailed introduction was necessary to provide the basis for the content of this training course. Nonetheless, exercise #1 (role-play) was conducted to enable participants to experience the initial non-agile state of the LEAD Factory. Further exercises performed were exercises #6 to #10 (see Table 40 and Table 41)

Table 50: Training action 2: part B – general information

Content	Date	Trainer	Data gathered	Participants
Module 3: **'strategic alignment'** - SC5: assess - SC6: define and create Module 4: **'governance'** - SC7: analyze and define - SC8: performance management	December 13th 2019	Author	- Pre-post knowledge test - Peer observation - Evaluation of intermediate training results - Questionnaire	Investigative group 2, n =16 - Mechanical engineering (n=11) - Computer science and software engineering (n=2) - Chemical engineering (n=1) - Business Administration (n=1) - Not named (n=1)

SC…Sub-competence; n…Number of participants

Pre-knowledge test results show similar to training action 1 ('part A') no substantial foreknowledge of participants. The post-test results show in general a positive impact. The impact of the training course related to sub-competence 5 shows an absolute increase of 56% in average of correct answers between pre and post test results. Similarily, results concerning question 5 addressing sub-competence 6, show an absolute increase of 61,7%. The content and importance of a playbook related question addressing sub-competence 7 achieved an absolute learning progress of 62%.

Table 51: Pre-post knowledge test results (part B)

	Question 4		**Question 5**		**Question 6**	
	Max. 4 points (=100%)		Max. 4 points (=100%)		Max. 4 points (=100%)	
	Pre	Post	Pre	Post	Pre	Post
Average points	0.07	2.31	0.29	2.75	0.64	3.13
Standard deviation	0.24	1.69	0.97	1.56	0.79	1.32
Average result [%]	1.8	57.8	7.1	68.8	16.1	78.1

Topic question 4: relevant core elements of corporations to with regard to agility (sub-competence 5: assess)
Topic question 5: agile operations lever categories (sub-competence 6: define & create)
Topic question 6: content and importance of a playbook (sub-competence 7: analyze & define)

Table 52 summarizes the key-statements from the obtained peer observation sheet. The statements show in correlation with the results of the pre-post knowledge test that participants' intermediate results ('observable actions') demonstrate satisfaction. Further, conducted exercises match well with learning objectives and the learning environment. However, it was mentioned that the business game conducted in its first version (single KPI as result, not linked to the learning factory activities of exercise #10) needs further considerations to better integrate virtual and physical learning experiences.

Table 52: Key-statements of peer observation protocol (part B)

Participants reaction	Learning environment, teaching methods and exercises
- Students kept being engaged (a lot of group discussion) - Motivation was high - Participants came up with good solutions - Student products demonstrate satisfaction concerning learning objectives - Need to ensure all students engage and speak up	- Experiments/exercises are well chosen and organized (realistic scenarios) - Experiments/exercises are important supplements to the course (match of theory and exercises) - Experiments/exercises develop intended learning objectives - Handouts and lecture notes are well organized - Debriefing tool 'timeline' valuable - Virtual ecosystem (business game) is valuable - Business game in more groups (participant engagement) - Business game result as single KPI needs reconsideration - Reflection on mix of shopfloor and classroom time required

The subjective observation of the author led to the same conclusion as the peer observation concerning the necessity to optimize the agile operations business game. Furthermore, the author recognized that a key element to agile operations - the lever categories - are not part of an explorative hands-on activity. Table 53 shows key-aspects of the subjective author observation and deviations to original planned training exercises during training conduction.

Table 53: Evaluation of intermediate results – observations by the author (part B)

Exercise	Duration (planned)	Deviation from expectation	Subjective assessment of author
Exercise #1	60 min.	Exercise was conducted as in training action #1 (part: A sensing)	- Target of (suboptimal) 'non-agile state' exploration achieved - Besides the clear transfer for the need for action exercise #1 works out as basis for 'to- be state' – modules 'governance' and 'strategic alignment'
Exercise #6 Exercise #7	75 min.	-	- Participants were not sure about target of this exercise - Participants did not explore core element of agile operations 'agile operations lever categories' on their own
Exercise #8	30 min.	Deviation of +20 minutes from original planned time	- Participants were very engaged in identifying possible agile operations levers and found good solutions - Scenario planning is missing and seems to be a valuable addition to this exercise - Additional information concerning future strategic target fields would increase relevance of this exercise

Exercise #9
Exercise #10
	105 min.	- Information (handout) was not prepared for exercise #10
		- Participants needed assistance with developing new roles and organizational structure
			- Elaborated playbooks by participants should be based on the chosen agile operations levers and on elaborated scenarios
			- The integration of the business game into the learning factory experience showed that:
			  - the correlation between the real timeline of events at the learning factory and the results of the business game (game rounds) was not given
			  - to ease the understanding showing just one KPI as result of agile operations is not sufficient
			  - the return on invested capital (ROIC) calculation with all its influencing parameters seemed to be too complex to understand for participants in detail

The questionnaire evaluation shows in general satisfactory results as it is perceived by the author. Results regarding item three indicate improvement potentials concerning exercise task descriptions. The relative low average value of items number six and twelve (below the level of 'agree') indicate too few parts of the training course dedicated to 'exploration'. The author assumes that one reason for the lower values for items six and twelve is the amount of time dedicated for the theoretical content of the introduction (teaching modules 1 and 2). Similar to training action 1 ('part: A'), participants' reaction indicate that opportunities to reflect are lacking (see Table 54).

Table 54: Questionnaire results (part B)

Factor	Item(s)	Objective of inquiry	Average points	Standard deviation
Constructive alignment	1,	Alignment between training course objectives, teaching methods and used media (Entwistle et al. 2003, p. 91)	**4.25**	**0.90**
	2,		**4.25**	**0.66**
	3,		**3.94**	**0.83**
	4		**4.44**	**0.70**
Stimulating tasks	5	Students perception of the importance of given problems in learning situations (Borglund et al. 2016, p. 10)	**4.50**	**0.61**
Exploration and own experience	6,	Contribution of participants experiences made within the training course to the overall learning process (Borglund et al. 2016, p. 10)	**3.75**	**0.56**
	7		**4.38**	**0.70**
Challenge	8	Perception of challenge of learning situations – challenging and stimulating but not overwhelming to students (Borglund et al. 2016, p. 10)	**4.44**	**0.61**
Understanding of the subject	9,	Deep understanding enforced through e.g. (1) relation of the course to prior knowledge; (2) link of subject matter to practical examples and (3) the support of learning activities to enhance key-concept understanding (Borglund et al. 2016, p. 11)	**4.25**	**0.66**
	10,		**4.38**	**0.48**
	11		**4.25**	**0.75**
Adequate prior knowledge	12	Have participants the necessary knowledge base or is this knowledge sufficiently addressed throughout the training course (Borglund et al. 2016, p. 12)	**3.63**	**1.17**
Time for reflection	13	Reflection opportunities of participants on their learnings throughout the course (Borglund et al. 2016, p. 12).	**3.75**	**0.75**
Collaboration	14	Opportunities for participants to collaborate (Borglund et al. 2016, p. 12)	**4.50**	**0.50**
Support	15	Opportunity for participants to get support in their learning from trainer/peer participants (Borglund et al. 2016, p. 12)	**4.56**	**0.50**

Number of participants = 16; answers from 1 (strongly disagree) to 5 (strongly agree)

Table 55 lists key-statements summarized from the open-ended questions to capture participants' reaction after the training course.

Table 55: Participants' comments on open-ended questions (part B)

General comments: **'best aspects of the course'**	- Experiences due to the combination of lecture and hands-on activities - The subject matter of agile operations itself - Learning environment (applicable and related topics) - Experiences related to different roles - Best-practice examples and implementation of agile operations levers (business game) - Exersices #1, #8 and #10 were named by participants as best training aspects
General comments: **'suggestions to improve'**	- More detailed exercise instructions - More time for exercises and for time to reflect - More detailed handout-material
Exercise #1	Very interactive and challenging
Exercise #6 **Exercise #7**	More time necessary
Exercise #8	Learn about example agile operations levers
Exercise #9 **Exercise #10**	- Interaction (business game approach) in this exercise was named twice as best aspect of the course - Link between business game and learning factory exercise not recognizable - Objective of the exercise lack details

6.3.3 Evaluation of action research cycle 1

As outlined in section 4.4.2 of this thesis, the author analyzed data source results first individually and subsequently triangulated the single data sets. The target was to identify improvement potentials. As previously described, there were no discrepancies across data sources.

Data of training action 1 (‘part: A’) shows that there is a need for action especially concerning ‘monitoring’ and with regard to opportunities to reflect on performed actions. Further, as peer observation and questionnaire results show, handouts and task descriptions need reconsideration. Figure 66 summarizes gained learnings linked to their origin data source.

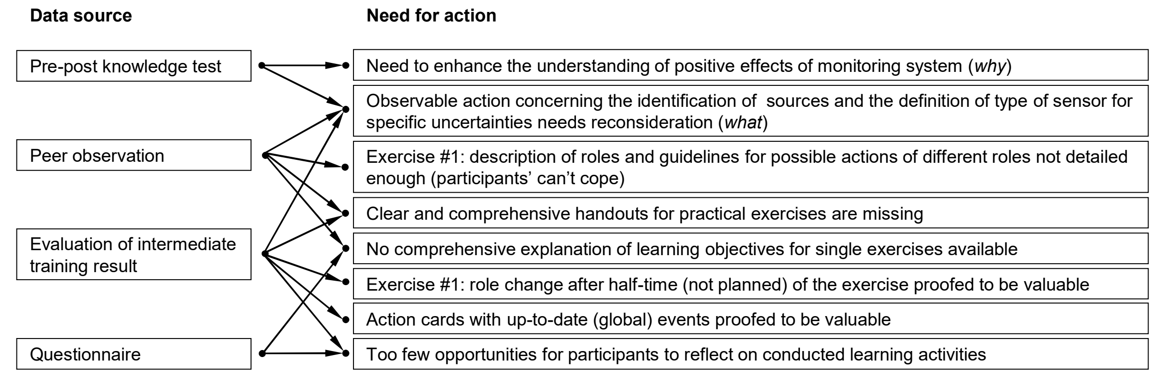
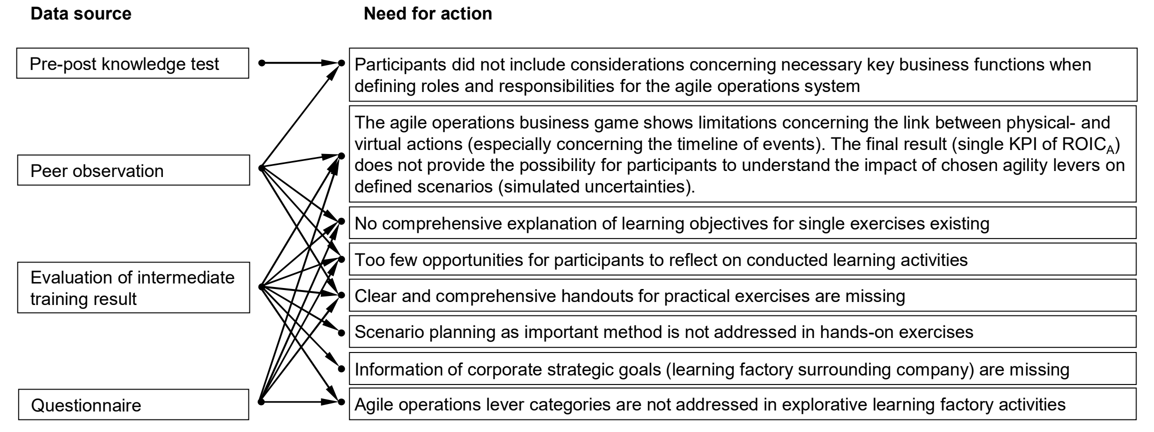


Figure 66: Derived need for action from collected data – training action 1 (part A) (own illustration)

The training action 2 (‘part: B’) addressed sub-competences regarding ‘strategic alignment’ and ‘governance’. Questionnaire results and the subjective author conclusion indicate to provide more explorative learning factory experiences and to expand existing exercises duration. The applied prototype of the agile operations business game needs adaptions according to participants’ reactions (open-ended questions), peer observation and the subjective assessment by the author. Especially the link between virtual actions (business game) and physical actions (learning factory) were not clear. Similar to training action 1, collected data demonstrates a need for action concerning expanding opportunities to reflect, clear and comprehensible handouts and better task descriptions (see Figure 67).



KPI…Key performance indicator; ROIC$_A$…Return on invested capital in agile operations measures

Figure 67: Derived need for action from collected data – training action 2 (part B) (own illustration)

To conclude, despite the initial goal of ‘testing’ and ‘learn’ of research cycle 1, the peer observers and the author agree that the quality of the learning activities (‘observable actions’) in combination with the gained knowledge (post-knowledge test) demonstrate the intended competence development. This applies for both conducted training actions (‘part A’ and ‘part B’) with the exception of ‘monitoring’ where the need for action is higher. However, data results of the pre-post knowledge test, participants’ reactions and peer observation in accordance with the subjective author assessment show that the learning environment (infrastructure, media, and applied teaching methods) do match in principle with the subject matter of agile operations. Derived learnings need to be addressed in action research cycle 2.

6.4 Action research cycle 2

As outlined in chapter 4, action research cycle 2 aims to develop and test implemented learnings from research cycle 1 and to identify further improvement potentials. First, this chapter describes elaborated adaptions (action based research phase ‘constructing’) based on findings of action research cycle 1. Second, it provides insights to results of the third training action. Finally, this section concludes with the evaluation of the conducted training action 3.

6.4.1 Adaptions to action research cycle 1

The author elaborated adaptions based on previously identified needs for action. Concerning teaching modules 1 and 2 (‘part: A’) the focus was especially on improving participants learnings related to ‘monitoring’. An additional exercise to derive *what* (events) and *how* (sensors) to monitor was elaborated (‘fault tree analysis’). Further, industry best-practice examples were included to the course to increase understanding *why* monitoring is valuable. The derived adaptions to teaching modules 3 and 4 focus on the development of a new exercise emphasizing the exploration of agile operations lever categories. This includes introducing a new product to the learning factory with different characteristics (e.g. dimensions, work tasks, employee qualifications). Second, the author further developed the agile operations business game. The target was to closer link the business game experience to the physical learning factory activities and to ease the understandability of lever impact for participants. Table 56 presents details concerning implemented adaptions based on action research cycle 1.

Table 56: Implemented adaptions – training modules ‘uncertainty’ and ‘monitoring’

Need for action	**Adaptions**
Need to enhance the understanding of positive effects of monitoring system (*why*)	Best-practice example of 2011 Fukushima crisis by Intel Corp. integrated (see *Sheffi 2015*)
Observable action concerning the identification of sources and the definition of type of sensor for specific uncertainties needs reconsideration (*what*)	Exercise to develop a decision tree (fault tree) for identified uncertainties to select potential sources and sensors integrated
Exercise #1: description of roles and guidelines for possible actions of different roles not detailed enough (participants’ can’t cope)	Role descriptions extended and ‘typical’ actions of different roles added
Clear and comprehensive handouts for practical exercises are missing	Consistent handouts for all exercises developed
No comprehensive explanation of learning objectives for single exercises available	Formulated learning objectives added to exercise descriptions
Exercise #1: role change after half-time (not planned) of the exercise proofed to be valuable	Update of trainer material (exercise description adapted)
Action cards with up-to-date (global) events proofed to be valuable	Update of trainer material (template for action cards implemented)
Too few opportunities for participants to reflect on conducted learning activities	More time for exercises and debriefing discussions planned

Table 57 shows implemented adaptions for the training modules 'strategic alignment' and 'governance'.

Table 57: Implemented adaptions – training modules 'strategic alignment' and 'governance'

Need for action	Adaptions
Participants did not include considerations concerning necessary key corporate elements when defining roles and responsibilities for the agile operations system.	Possible roles and related actions to support agile operations are suggested during the exercise explanation (process and objectives of exercise)
The agile operations business game shows limitations concerning the link between physical- and virtual actions (especially concerning the timeline of events). The result (single KPI of ROIC$_A$) does not provide the possibility for participants to understand the impact of chosen agility levers on defined scenarios (simulated uncertainties).	The agile operations business game was further developed: (1) Round-based simulation of events in accordance to the physical learning factory exercise (2) Round-based depiction of products produced (agile vs. non-agile state) in comparison to demand volatility (3) Round-based and accumulated calculation of the 'ROIC$_A$' KPI
No comprehensive explanation of learning objectives for single exercises existing	Formulated learning objectives added to exercise descriptions
Too few opportunities for participants to reflect on conducted learning activities	More time for exercises and debriefing discussions planned
Clear and comprehensive handouts for practical exercises are missing	Consistent handouts for all exercises developed
Scenario planning as important method is not addressed in hands-on exercises	Scenario planning integrated in exercises #7 and #8
Information of corporate strategic goals (learning factory surrounding company) are missing	A product-market-matrix ("Ansoff Matrix") was elaborated and integrated in the exercise information to provide information about corporate strategic goals
Agile operations lever categories are not addressed in explorative learning factory activities	Exercise elaborated (exercise #5) to identify (and categorize) elements of operations to adapt when changing to a different product (new product – e-Scooter - added to the learning factory)

KPI…Key performance indicator; ROIC$_A$…Return on invested capital in agile operations measures

6.4.2 Training course 'design an agile operations system'

After planning and implementing changes to the course setup, training action 3 started on March 05th 2020. Training action 4 was conducted on March 03rd and 04th 2021. The investigative groups of action research cycle 2 conducted both training parts of 'sensing' and 'responding' in two consecutive days at the LEAD Factory (see chapter 4.4). Appendix H provides the detailed course schedule. Table 58 provides general information of these training actions.

Table 58: Training actions 3 and 4: general information

Content	Date	Trainer	Data gathered	Participants
Module1: **'uncertainty'** Module 2: **'monitoring'** Module 3: **'strategic alignment'** Module 4: **'governance'**	March 05-06, 2020	Author	- Pre-post knowledge test - Peer observation - Evaluation of intermediate training results - Questionnaire	Investigative group 3, n=12 - Computer science and software engineering (n=6) - Mechanical engineering (n=3) - Chemical engineering (n=2) - Civil engineering (n=1)
Module1: **'uncertainty'** Module 2: **'monitoring'** Module 3: **'strategic alignment'** Module 4: **'governance'**	March 03-04, 2021	Author	- Pre-post knowledge test - Peer observation - Evaluation of intermediate training results - Questionnaire	Investigative group 4, n =8 - Mechanical engineering (n=7) - Computer science and software engineering (n=1)

The difference of pre-test results inbetween the two investigative groups of action research cycle 2 were below 10% variance. The post knowledge test results were notably different for questions 3 (difference of average results of 25%) and 4 (difference of 63%). Expecially the result of question 4 at training action 3 with an absolute increase of 4,2 % is considerably lower than all other results including comparable results of action research cycle 1 (question 4 achieved in action research cycle 1 an absolute increase of 57%). The second group achieved an average absolute knowledge increase of 63% at question 4. Table 59 provides the overview of the combined average pre-post knowledge test results of investigative groups 3 and 4.

Table 59: Pre-post knowledge test results

	Question 1		**Question 2**		**Question 3**	
	Max. 6 points (=100%)		Max. 4 points (=100%)		Max. 5 points (=100%)	
	Pre	Post	Pre	Post	Pre	Post
Average points	0.40	5.20	0.10	2.60	0.20	2.25
Standard deviation	0.80	1.54	0.30	1.56	0.40	1.44
Average result [%]	6.70	86.7	2.5	65.0	4.0	45.0
	Question 4		**Question 5**		**Question 6**	
	Max. 4 points (=100%)		Max. 4 points (=100%)		Max. 4 points (=100%)	
	Pre	Post	Pre	Post	Pre	Post
Average points	0.45	1.50	0.15	3.80	0.15	2.20
Standard deviation	0.59	1.60	0.48	0.51	0.36	1.03
Average result [%]	11.3	37.5	3.8	95.0	3.8	55.0

Topic question 1: origin areas of uncertainty (sub-competence 1: identify & structure)
Topic question 2: impact of uncertainties on operations (sub-competence 2: analyze & prioritize)
Topic question 3: functions and benefits of a monitoring system (sub-competence 3: analyze, define & select)
Topic question 4: relevant core elements of corporations to with regard to agility (sub-competence 5: assess)
Topic question 5: agile operations lever categories (sub-competence 6: define & create)
Topic question 6: content and importance of a playbook (sub-competence 7: analyze & define)

Peer observation results point out that motivation of participants was even higher than in previous training actions. Further, the continuous flow of the training held in two consecutive days contributed to a logic sequence of participants' actions throughout the different exercises. Concerning adaptions made, peer observation results positively point out that opportunities to reflect were increased (more exercise time, intermediate discussions), course handouts enabled a better understanding of exercise tasks, the new developed exercise #5 proofed to be valuable and that the further developed business game had a positive impact on exercise #10. However, adaptions made concerning the statement of learning objectives and the significant changed exercise #4 (monitoring) did not show the improvements actually assumed by the author.

Table 60: Key-statements of peer observation protocol (action research cycle 2)

Participants reaction	Learning environment, teaching methods and exercises
- Students kept being engaged (a lot of group discussion) - Motivation was high (even higher than in action research cycle 1) - Participants took exercises seriously (role immersion) - Student products demonstrate satisfaction concerning learning objectives - Students carried out solutions from the beginning to the end in a series of logic steps despite not providing too much information/help - More time for exercises and intermediate discussions contribute to a better understanding	- Experiments/exercises are well chosen and organized (realistic scenarios) - Experiments/exercises are important supplements to the course (match of theory and exercises) - Experiments/exercises develop intended learning objectives - Learning objectives could be stated more prominent - Handouts and lecture notes are well organized (improved in relation to action research cycle 1) - Exercise #5 (exploration of lever categories) was valuable to participants understanding - Exercise #10 improved due to the further developed agile operations business game - Exercise #2 too long - Exercise #4 needs better explanation – at least one prepared example of the fault tree analysis is needed - Exercise #6 too short (time) and needs better explanation/introduction

Table 61 lists the key observations made by the author for each exercise. Similar to other data gathering methods, the author identified a need for action to further improve the monitoring exercise despite taken adaptions.

Table 61: Observations by the author (action research cycle 2)

Exercise	Duration	Deviation from expectation	Subjective assessment of author
Exercise #1	75 min.	-	Extended role descriptions worked out well
Exercise #2	60 min.	-	Results of group work and discussion demonstrated the intended target
Exercise #3	60 min.	-	Participants understand the interrelation from exercise #1, #2 and #3
Exercise #4	75 min.	Task description was not clear (students required guidance)	- Participant did not understand the necessity for the fault tree analysis in relation to the monitoring system - Exercise results were not satisfactory
Exercise #5	45 min.	-	- Participants were very engaged - Despite that this exercise was conducted at the learning factory shopfloor, participants did include external dependencies (e.g. supplier)
Exercise #6	30 min.	Task description was not clear (students required guidance)	Participants did not see the consistency from exercise #1 to exercise #5 and exercise #6
Exercise #7	75 min.	-	- Exercise #5 had a positive impact on participants' results (agile operations lever identification) - Scenario planning enforces the understanding for the need of combining levers
Exercise #8	75 min.	Not all participants used their results from exercises #2 and #3 as basis	- Participants were very engaged discussing potential lever combinations (business game) - The additional information concerning strategic goals ('Ansoff-Matrix') contributed to the discussions
Exercise #9	45 min.	-	Scenario planning (exercise #7) positively influenced the outcome (playbook)
Exercise #10	75 min.	-	- Monitoring system worked out well - Link between physical learning factory and virtual business game exceeded expectation - Debriefing discussion exceeded expectation

The post-training questionnaire results demonstrate in general a high acceptance concerning the combination of the subject matter of agile operations and the learning factory based learning environment. Each objective of inquiry was positively confirmed with at least an average score of 3,9 or higher (see Table 62).

Table 62: Questionnaire results (action research cycle 2)

Factor	Item(s)	Objective of inquiry	Average	Standard deviation
Constructive alignment	1,	Alignment between training course objectives, teaching methods and used media (Entwistle et al. 2003, p. 91)	**4.60**	**0.49**
	2,		**4.50**	**0.50**
	3,		**4.15**	**0.73**
	4		**4.55**	**0.59**
Stimulating tasks	5	Students perception of the importance of given problems in learning situations (Borglund et al. 2016, p. 10)	**4.60**	**0.58**
Exploration and own experience	6,	Contribution of participants experiences made within the training course to the overall learning process (Borglund et al. 2016, p. 10)	**4.45**	**0.50**
	7		**4.45**	**0.59**
Challenge	8	Perception of challenge of learning situations – challenging and stimulating but not overwhelming to students (Borglund et al. 2016, p. 10)	**4.45**	**0.59**
Understanding of the subject	9,	Deep understanding enforced through e.g. (1) relation of the course to prior knowledge; (2) link of subject matter to practical examples and (3) the support of learning activities to enhance key-concept understanding (Borglund et al. 2016, p. 11).	**4.60**	**0.49**
	10,		**4.60**	**0.58**
	11		**4.65**	**0.57**
Adequate prior knowledge	12	Have participants the necessary knowledge base or is this knowledge sufficiently addressed throughout the training course (Borglund et al. 2016, p. 12).	**4.35**	**0.96**
Time for reflection	13	Reflection opportunities of participants on their learnings throughout the course (Borglund et al. 2016, p. 12).	**3.90**	**0.83**
Collaboration	14	Opportunities for participants to collaborate (Borglund et al. 2016, p. 12)	**4.70**	**0.56**
Support	15	Opportunity for participants to get support in their learning from trainer/peer participants (Borglund et al. 2016, p. 12).	**4.90**	**0.30**

Number of participants = 20; answers from 1 (strongly disagree) to 5 (strongly agree)

Participants highlighted the impact of the agile operations system on the learning factory setup (non-agile state vs. agile state). Further, participants suggested to increase time for decision-making (exercise #8) and to add a post-action discussion (exercise #10) with regard to the agile operations business game.

Table 63: Participants' comments on open-ended questions (action research cycle 2)

General comments **'best aspects of the course'**	- Gamification elements (agile operations business game) - Using the tools – especially the monitoring system - Possibility to observe different functions and how to deal with new and different situations - Experiences due to the combination of lecture and hands-on activities - Working on real scenarios - Very well structured course
Exercise #1 **Exercise #10**	Experience the difference of the non-agile state (exercise #1) and agile state (exercise 10) had the most impact
Exercise #8	Provide more time for the decision-making process concerning the agile operations business game
Exercise #10	Dedicate time to reflect for participants after the hands-on learning factory experience to analyze physical and virtual results

6.4.3 Evaluation of action research cycle 2

Overall, data triangulation across the conducted training actions showed one major discrepancy at the results of investigative group 3. The pre-post knowledge test average result in correct answers of question 4 ('core elements to an agile operations system') significantly differs in group 3 from the other investigative groups and from observations made by the peer observer and the author. Especially exercises related to 'defining' an agile operations system (lever identification, elaboration of an agile operations playbook, defining responsibilities) did not show as bad quality in terms of intermediate results as the author would expect due to the low knowledge test result concerning question 4. A main reason for this discrepancy could be a general misunderstanding of terms as participants answers did go noticeably in the same (wrong) direction at the training course with investigative group 3. However, due to this discrepancy, further investigations (i.e. repeated application of the learning factory training course) are suggested.

One aim of action research cycle 2 was to test derived developments. Table 64 summarizes the impact of implemented adaptions derived in action research cycle 1 on participants' activities based on collected data.

Table 64: Evaluation of implemented adaptions

Focus of adaptions	**Impact on participants activities**
Task descriptions and additional exercise information	+ Comprehensive task descriptions supported self-dependent work of participants + Ansoff Matrix with strategic corporate goals provided a solid basis for exercises related to 'defining agility'
Handouts	+ Provided to participants a comprehensive guide across all exercises
Learning objectives	~ Participants did focus solely on the concrete task description and not on formulated learning objectives listed directly below
Monitoring	~ Adaptions did not significantly enhance participants understanding related to *what* to monitor or *why* monitoring is needed - Participants were not able to elaborate given task without guidance (exercise #4 - fault tree analysis)
Opportunities to reflect	+ Optimized time management of exercises proofed to be valuable + Guided intermediate discussions increased participants understanding
Business game	+ Round-based event simulation linked virtual business game closely to the physical learning factory activities + Debriefing discussion benefited from the resulting timeline of products produced versus demand volatility and the development of the $ROIC_A$ KPI
Scenario planning	+ Including the scenario planning method in exercise #7 did improve results of exercises related to 'defining agility' + Contributed especially to participants understanding for the need of lever combinations
Key corporate elements/functions for agile operations	n.a. Discrepancy between post-test results and observations by both, peer and author, do not allow a meaningful statement of the impact on participants activities

-…negative impact; ~…neutral impact; +…positive impact; n.a.…not applicable

The second aim of action research cycle 2 was the identification of further needs for action to continuously improve the training course. As aforementioned, especially adaptions related to 'monitoring' did not show a satisfactory impact.

Figure 68 presents further areas of improvement.

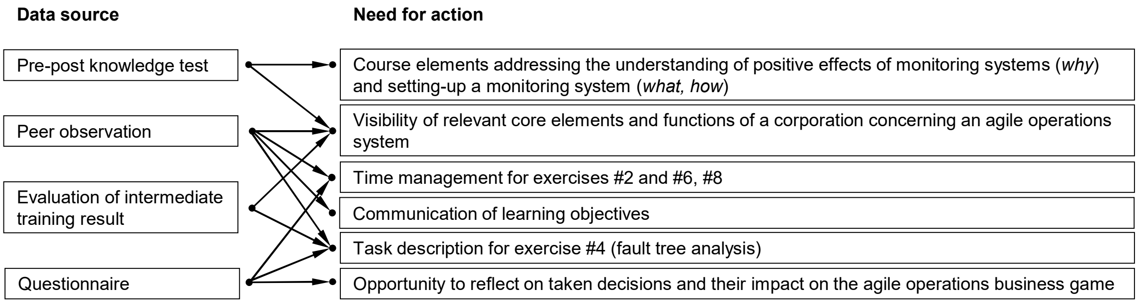


Figure 68: Derived need for action from collected data (action research cycle 2) (own illustration)

As outlined in section 4.4.1, the scope of this research was limited to two research cycles due to existing constraints (time and accessibility). However, the shortcomings identified in action research cycle 2 contribute to the outlook of this research study.

6.5 Interim conclusion: Agile operations at the LEAD Factory

The author chose to apply the developed training course to design an agile operations system at Graz University of Technology's learning factory ('LEAD Factory'). The available infrastructure (focus on assembly tasks), the product processed (market-available scooter in three variants) and the underlying didactical concept (three maturity stages: as-is state, lean state and digital state) of the learning factory provided an adequate basis. In this research study the derived agile operations related extensions (see section 5.5) were developed based on processes and products of the LEAD Factory to establish the new required maturity stage ('agile state').

As outlined in chapter 4, this research study conducted two research cycles following the chosen action based research approach. However, as this research study investigates competence development of individuals it is dependent on person-related confounding variables (e.g. prior knowledge, previous experiences, personal learning style, personal motivation) and environmental or study-related confounding variables (e.g. different treatment of groups by the trainer) (Döring and Bortz 2016, p. 196).

The pre-post knowledge test aimed to obtain insights into actual learnings of participants. Prior knowledge was in a similar range across all participant groups and knowledge related questions. Retrieved results indicate that conducted adaptions had a positive influence on knowledge related to question 1, question 2, question 3 and question 5. The results concerning question 4 and question 6 show a negative development from action research cycle 1 to research cycle 2. The deviation of results regarding question 4 are addressed in section 6.4.3.

However, results of the pre-post knowledge test show in both research cycles a substantial increase of knowledge (see Table 65) with the exception of question 4 in research cycle 2 as aforementioned. This statement is supported by comparing the results of a similar study conducted by *Cachay et al. 2012*. The authors investigated the learning success achieved in a learning factory compared to a conventional lecture setting. The learning success was measured similarly using a pre-post knowledge test and showed an absolute increase of about 30% per each test question. (Cachay et al. 2012, p. 1150)

Table 65: comparison of pre-post knowledge test results

		Absolute increase of correct answers from pre- to post test results in [%]		
Question		**ARC 1**	**ARC 2**	**Delta** [%]
1	Origin areas of uncertainties (SC1: identify & structure)	63.0	80.0	**+17.0**
2	Impact of uncertainties on operations (SC2: analyze & prioritize)	58.9	62.5	**+ 3.6**
3	Functions and benefits of a monitoring system (SC3: analyze, define & select)	30.0	41.0	**+ 11.0**
4	Relevant core elements of corporations with regard to agility (SC5: assess)	56.0	26.3	**- 29.8**
5	Agile operations lever categories (SC6: define & create)	61.7	91.3	**+ 29.6**
6	Content and importance of a playbook (SC7: analyze & define)	62.0	51.3	**- 10.8**

ARC…Action research cycle; SC…Sub-competence

Nevertheless, pre-post knowledge test results allow only limited conclusions to be drawn. Observations by peers and the author provided valuable insights concerning the applied methods at the learning environment and the competence development of participants. In both action research cycles peer observation led to the identification of further needs for action. In addition, peer observation confirmed the positive influence of developed elements and the implemented adaptions applied in action research cycle 2. Examples are the positive impact of the further developed agile operations business game or the positive impact of measures to provide participants with more opportunities to reflect on taken actions. In general, it highlighted especially the high engagement and motivation of participants throughout the training actions.

As defined in chapter 2.3, competences are not directly measurable. However, by observing defined actions in combination with available knowledge, competences can be assessed. Despite the one outlier of the pre-post knowledge test result (question 4, action research cycle 2) there were no discrepancies between the different data gathering methods. After evaluating the results, the peer observer and the author separately assessed the knowledge gained and the actions observed. Table 66 shows the results concerning the question to what extent the intended competences were observable.

Table 66: Assessment of intended competence development for action research cycle 2

		Competence observed*	
Sub-competence		Peer observer	Author
1	…**identify** and **structure** external and internal uncertainties on different business levels.	**5**	**5**
2	…**analyze** and **prioritize** the impact of identified uncertainties on operations according to the need for action.	**5**	**5**
3	…**analyze**, **define** and **select** requirements and sensors to early detect external and internal uncertainties	**5**	**4**
4	…**structure** and **generate** a monitoring report for decision makers to early react on uncertainties.	**4**	**4**
5	…**assess** current operations regarding agility.	**4**	**5**
6	…**define** and **create** the appropriate agility need level for operations.	**5**	**5**
7	…**analyze** and **define** roles and responsibilities in a corporate agility system relevant to operations.	**4**	**4**
8	…are familiar with an appropriate performance management for the concept of agile operations.	**4**	**4**

* answers from 1 (strongly disagree) to 5 (strongly agree)

In general, data from the post-training questionnaire was aligned with the other data collection methods. Results showed a broad acceptance of the learning factory setting in combination with the subject matter of agile operations from the participants' point of view. Further, questionnaire results provided valuable insights concerning the need for further developments and their impact. Especially the item that inqueried opportunities to reflect did improve from action research cycle 1 to research cycle 2.

6.6 Quasi-experiment

The author chose to conduct a quasi-experiment (see section 4.4.2) comparing two different teaching methods (learning factory treatment and lecture treatment). However, as pointed out in section 4.1, this study does not intend to proof that one teaching method is superior to another method. Rather, the quasi-experiment aimed to contribute to the discussion of the research questions. Data collected in this experiment (pre-post knowledge test; questionnaire) allows solely conclusions about the knowledge transfer and participants reaction on the elements of the respective treatment. Collected data does not enable to compare developed competences, as the lecture-group did not apply theoretical gained knowledge in the learning factory ('observable actions' – see section 5.2). Further, personal-related and environmental- or study-related confounding variables limit the validity of conclusions.

The investigative group consists of the learning factory training actions (n= 20) conducted in action research cycle 2. The frontal lecture group consists of 39 students enrolled to the master program mechanical engineering and economics (or similar). Table 67 provides details on the conducted experiment.

Table 67: Quasi-experiment details

	Investigative groups		
	Training action 3	**Training action 4**	**Frontal lecture group**
Participants	n=12	n=8	n=39
Duration	2-days (03-05/06-2020)	2-days (03-03/04-2021)	4 hours (01-04-2020)
Trainer/lecturer	Author	Author	Author
Treatment	- Theory - Learning factory exercises	- Theory - Learning factory exercises	Theory
Data gathered	- Pre-post knowledge test - Questionnaire	- Pre-post knowledge test - Questionnaire	- Pre-post knowledge test - Questionnaire*

* applicable items only (e.g. no items regarding exercise experiences); n…Number of participants

The pre-post knowledge test results show differences between the two treatments. Every single post-question result shows a higher average value of correct answers in the investigative groups than in the frontal lecture group. Especially questions regarding the origin areas of uncertainties (question 1); agile operations lever categories (question 5) and the agile operations playbook (question 6) indicate that the learning factory treatment enhanced the respective know-how transfer. The pre-test results were comparable for the questions 1 to 5 were the difference was at maximum 0,3 points of average correct answers between the two different treatments. Solely the pre-test result concerning question 6 was with 20,8% of correct answers in average considerably higher than in the investigative groups with an average of 3,8% of correct answers.

Figure 69 shows the comparison of investigative group and frontal lecture group post-test results.

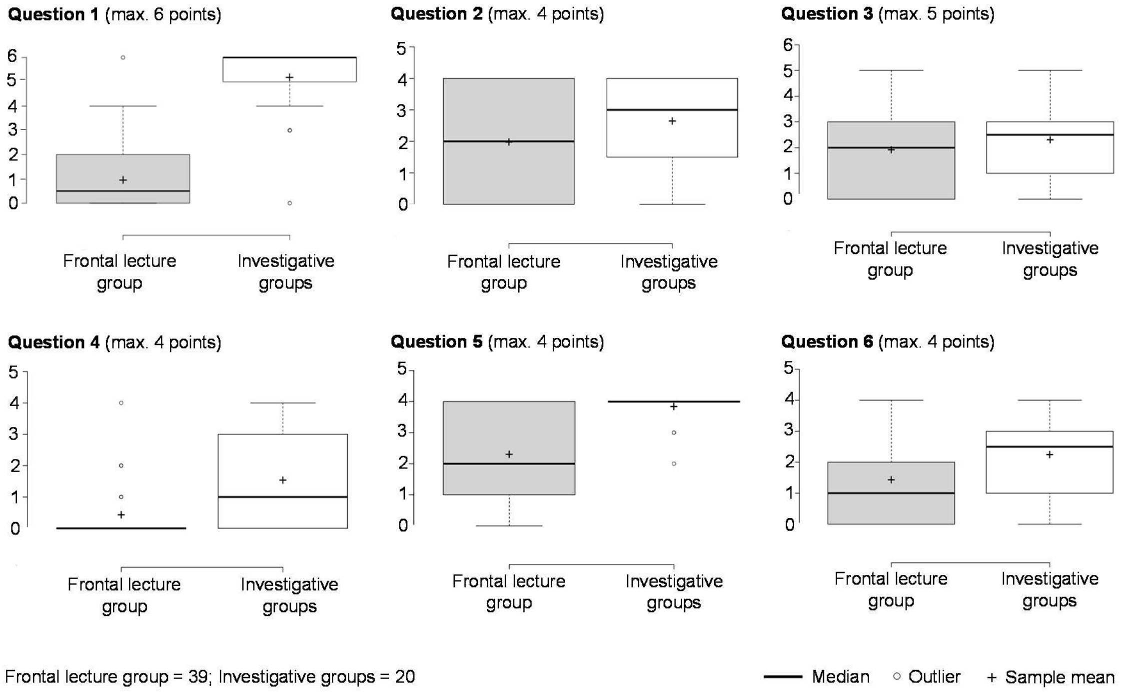


Figure 69: Derived need for action from collected data (action research cycle 2) (own illustration)

From a participants point of view the post-questionnaire inquiry indicates that especially the aspects of the match of subject content and learning environment, the opportunities to reflect, experiences made, the motivation and collaboration promote the learning factory based training course. Further, participants perceived the learning situations created at the LEAD Factory as more challenging and stimulating. Similar to the knowledge test results, there was no objective of inquiry higher rated in average in the frontal lecture group than in the investigative groups. Table 68 shows the comparison of the questionnaire results for the two different experiment setups.

However, besides the non-randomized study setup there are further limitations related to these results. First, the frontal lecture groupt did undergo a four hour treatment whereas the investigative groups were engaged in total for two days at the learning factory. Second, as the frontal lecture group did not apply the gained knowledge solely theoretical knowledge could be compared and not actual intened competences. Furthermore, a comparison of the gained knowledge over a longer period of time would be of interest (e.g. a further knowledge test after 3 months).

Table 68: Questionnaire results of the quasi-experiment

		Frontal lecture[1]	LF[2]	LF compared to frontal lecture*
Item(s)	**Objective of inquiry**	**AVG points** (SD)	**AVG points** (SD)	
1,	Alignment between training course objectives, teaching methods and used media (Entwistle et al. 2003, p. 91)	**3.62** (0.70)	**4.60** (0.49)	**+20%**
2,		**3.90** (0.63)	**4.50** (0.50)	**+12%**
3,		n.a.	**4.15** (0.73)	
4		n.a.	**4.55** (0.59)	
5	Students perception of the importance of given problems in learning situations (Borglund et al. 2016, p. 10)	**4.10** (0.74)	**4.60** (0.58)	**+10%**
6,	Contribution of participants experiences made within the training course to the overall learning process (Borglund et al. 2016, p. 10)	n.a.	**4.45** (0,50)	
7		**2.82** (1.03)	**4.45** (0.59)	**+33%**
8	Perception of challenge of learning situations – challenging and stimulating but not overwhelming to students (Borglund et al. 2016, p. 10)	**3.26** (0.93)	**4.45** (0.59)	**+24%**
9,	Deep understanding enforced through e.g. (1) relation of the course to prior knowledge; (2) link of subject matter to practical examples and (3) the support of learning activities to enhance key-concept understanding (Borglund et al. 2016, p. 11).	**3.92** (0.76)	**4.60** (0.49)	**+14%**
10,		**3.77** (0.86)	**4.60** (0.58)	**+17%**
11		**3.72** (0.88)	**4.65** (0.57)	**+19%**
12	Have participants the necessary knowledge base or is this knowledge sufficiently addressed throughout the training course (Borglund et al. 2016, p. 12).	**4.00** (0.85)	**4.35** (0.96)	**+7%**
13	Reflection opportunities of participants on their learnings throughout the course (Borglund et al. 2016, p. 12).	**2.46** (0.93)	**3.90** (0.83)	**+25%**
14	Opportunities for participants to collaborate (Borglund et al. 2016, p. 12)	**2.87** (1.09)	**4.70** (0.56)	**+37%**
15	Opportunity for participants to get support in their learning from trainer/peer participants (Borglund et al. 2016, p. 12).	**3.97** (0.73)	**4.90** (0.30)	**+19%**

AVG…Average; SD…Standard deviation; LF…Learning factory, n.a. … not applicable

[1] Number of participants = 39

[2] Number of participants = 20

* 100% = 5 (5-point Likert-scale)

CHAPTER 7
Conclusion

This chapter first answers the formulated research questions. Second, it discusses the research quality of the present research study taking into account aspects of validity, reliability and objectivity.

7.1 Main findings

The main purpose of this research study was to enable competence development regarding the design of an agile operations system to cope with uncertainty in operations. Further, it was defined that a learning factory is to be used for this competence development. This section presents the author's interpretations of the results obtained throughout this research study. In the following, the two main research questions are answered.

RQ 1: What characterizes a learning factory based training concept that supports competence development regarding the design of an agile operations system?

Based on the conducted literature study (chapter 2) following key-elements form the basis for the developed training concept:

- **Understand the business environment** – Taking a pro-active approach to understand agility drivers and their impacts on operations are the pre-requisite for agile operations
- **Monitor the business environment** – The early detection of problems or opportunities is the basis to react fast and achieve a competitive advantage
- **Pro-active alignment** – Defining a suitable agile operations company need level to synchronize internal processes with uncertain developments (via agile operations levers) leads to faster resource re-allocation
- **Operational control** – Governance ensures the orchestration of the continuous identification of needs for action as well as effective decision-processes to adjust the agile operations level

The main competence (classified as professional and methodological competence) was formulated based on the derived understanding of the concept of agile operations and reads as follows:

Participants of the agile operations training are able to design an agile operations system to cope with uncertainty in operations.

This main competence was operationalized by defining sub-competences consisting of observable actions and knowledge elements addressing the '*how*', '*what*', '*when*' and '*why*'. Sub-competences were formulated based on identified knowledge elements in literature. The following list presents the eight sub-competences related to the derived key-elements of the agile operations concept.

Participants of the agile operations training are able to:

- **Identify** and **structure** external and internal uncertainties on different business levels
- **Analyze** and **prioritize** the impact of uncertainties on operations according to the need of action
- **Analyze**, **define** and **select** requirements and sensors to early detect external and internal uncertainties
- **Structure** and **generate** a monitoring report for decision makers to early react on uncertainties
- **Assess** current operations regarding the capability of coping with uncertainties
- **Define** and **create** the appropriate agility need level for operations
- **Analyze** and **define** roles and responsibilities in a corporate agility system
- **Apply** an appropriate performance management for the agile operations system

The derived sub-competences highlight again the broad scope of an agile operations system, which is subsequently responsible for the requirements on the learning environment.

The learning factory principle comprises a close-to-reality abstraction of an industrial value stream (see chapter 2.4). Requirements of agile operations addressing e.g. external developments, supply chain partners or production network related activities interfere with learning factory limitations identified in literature:

- **Resource-related limitations** – Learning factories are resource intensive and need to consider resource feasibility especially when it comes to depicting upper factory levels
- **Time-related limitations** – Participants experiences are based on immediate feedback from the learning environment on performed actions
- **Solution-related limitations** – The solutions derived by participants to install an agile operations system need to be implementable throughout the training course

To enable the integration of the whole scope of agile operations the author developed so-called ‘extensions’ (such as the agile operations business game) to a ‘classic’ learning factory (see chapter 5.5). These extensions enable participants to experience the impact of uncertainties (negative and positive challenges) as well as the impact of an implemented agile operations system on operations. Established experiential teaching methods and identified approaches related to this research study were the basis for the development of a fictional business environment (case study), a role-play, a technical monitoring system abstracted for the use in a learning factory and an agile operations business game. The following Table 69 characterizes the developed extensions.

Table 69: Characteristics of agile operations specific learning factory extensions

Extension	**Characteristics**
Case study: fictional business environment	- Information about production program - Defined suppliers, production network and sales channels - Detailed information about logistics (inbound & outbound) - Detailed customer analysis - Information about the fictional learning factory company (e.g. strategy)
Role-play	- Predefined roles: worker, operations manager, purchasing manager, general manager - Detailed specific information for each role (e.g. purchasing manager – inventory level) - Each role is provided with possible actions to take and objectives to fulfill throughout the exercise
Monitoring system	- To monitor the fictional business environment the developed monitoring system is based on RSS Feeds - Participants identify and prioritize uncertainties, define trigger points and set-up the monitoring system using specific keywords and keyword combinations - Participants experience with ‘fast detect’ a key aspect of agile operations system
Business game	- Based on a business game approach are the effects of uncertainties on operations and the impact of countermeasures (agile operations levers) depicted - To model the fictional company (linking operational performance with financial KPIs) as KPI-tree is used as basis - Participants analyze the business environment, the fictional learning factory company, define a suitable agility need level and decide on the implementation of agile operations levers to cope with uncertainties - The success of participants and their chosen agile operations lever combination is shown as “matching the demand curve” and the achieved return on invested capital per agility (‘ROIC$_A$’)

KPI…Key performance indicator; ROIC$_A$…Return on invested capital in agile operations measures

The learning factory at Graz University of Technology (‘LEAD Factory’) was chosen to apply the developed training course. In total 50 participants took part in four agile operations trainings. Consulted literature points out that to evaluate the development of a certain competence its sub-competences, respective knowledge elements and performed actions must be assessed (see e.g. Glass and Metternich 2020, p. 39). Therefore, the collected data throughout this study comprised a combination of knowledge tests and the observation of taken actions (see section 4.4.2 for details about the data collection and analysis approach).

The introduced results showed that the knowledge transfer measured with a pre-post knowledge test approach was in line with or exceeded prior study results. As described, this is especially true considering a similar study measuring the learnings of a learning factory based course by *Cachay et al. 2012*. Along with the peer observation and the author assessment of intermediate results and taken actions the outcomes of this research study point out that participants of investigative groups 3 and 4 (action research cycle 2) developed the intended (sub-)competences. Subsequently, the author concludes that the developed training course enables the competence development of participants regarding the design of an agile operations system. However, this research study has its limitations, which are discussed in following chapter 7.2.

The three main characteristics of the developed training concept are:

- **Authentic problem situation** – Participants deal with a real and tangible problem in an experiential learning environment
- **Alternation of thinking and doing** – Short intertwined theory sessions provide input for hands-on actions conducted by participants or serve as 'systematization' elements of made experiences
- **Opportunities to reflect** – Participants structure and analyze made experiences to create new problem solutions based on their findings

It can be concluded, that research question 1 was answered by the formulation of (sub-)competences, the derivation of requirements of the subject matter of agile operations on the learning environment, the development of so-called learning factory extensions to overcome learning factory limitations, the application of the developed training course and therefrom obtained results that confirm the intended competence development

RQ2: How does the concept 'learning factory' support competence development regarding the design of an agile operations system?

Consulted literature highlights the 'learning factory principle'. Learning factories are complex systems enabling a diverse alternation of understanding, application and reflection processes especially in the field of production process optimization (see e.g. Abele et al. 2010b, p. 909; Cachay and Abele 2012, p. 639; Tisch 2018, p. 60). This research study aimed to 'match' the subject matter of agility in operations and its broad scope with the learning factory principle. Overall, the results of the questionnaire items (measuring participants reactions) addressing the alignment between training course objectives, teaching methods and used media show the 'fit' between the learning factory based setting and the subject matter of agile operations. The respective items achieved at least in average 4,15 points on the 5-point Likert scale (from 1 strongly disagree to 5 strongly agree). This, and all of the following results presented in this section belong to actions taken in research cycle 2.

Authentic problem situation

The learning factory system (according to the narrow definition by *Abele 2018*) provides with the physical product and the respective production system the basis for the authentic problem situation. This research study introduced previously described extensions (see Table 69) to the learning factory principle to overcome identified limitations of learning factories interfering with the broad scope of the subject matter agile operations. However, the 'classic' learning factory elements (products, processes, and infrastructure) form the basis for these extensions (e.g. product defining the fictional supply chain or product/ processes/infrastructure defining the company model of the agile operations business game).

Results of the present study show that participants perception of the importance of the problems in the learning factory with an average value of 4,60 (SD: 0,5) on the 5-point Likert scale was given. Further, participants' reaction to the questionnaire item related to the 'perception of challenge of learning situations – challenging and stimulating but not overwhelming to students' (average points: 4,45, SD: 0,59) shows the positive impact of the learning factory environment on providing an authentic problem situation. The conducted quasi-experiment further shows that both of these values are lower rated in the comparing lecture group.

Alternation of thinking and doing

Consulted literature points out that potentials of learning factories include amongst others the combination of thinking and doing and the activation of learners (see section 2.4.3). The learning factory principle builds upon two maturity stages ('non-agile state' → 'agile-state') with the requirement that participants are able to implement their own solutions. This principle contributes to participants' actions ('doing').

Further, the course (exercise-)sequences were conceptualized to support the alternation of thinking (theoretic introduction and systematization elements) and doing (experimentation and exploitation elements) – see chapter 5.4.

Study results show that participants acknowledge the contribution of their made experiences in the learning factory on their overall learning process (respective items achieved at least 4,45 points in average on the 5-point Likert scale; SD: 0,59). Further, items addressing the link between the subject matter and practical examples as well as the support of learning activities to enhance concept understanding show the positive impact of the applied methods (respective items achieved at least 4,60 points in average on the 5-point Likert scale; SD: 0,58). The quasi-experiment results of the frontal lecture group were substantially lower rated in these items. Further, peer observation protocols highlight the high motivation and engagement of participants throughout the conducted learning factory training actions.

Opportunities to reflect

The learning factory principle comprises versatility and flexibility of its infrastructure to enable the 'real' application of analysis, planning and implementation processes (see e.g. Reiner 2009, p. 85). To enable the mapping of the broad scope of agile operations the author developed the previously described learning factory extensions. Concerning participants' reflection, this includes besides 'real' learning factory actions (hands-on activities) virtual actions causing partly 'real' and virtual effects contributing to participants' experiences. Participants' reactions showed initially a need for action concerning opportunities for reflection. However, implemented adaptions led to an increase in the questionnaire item addressing the availability of opportunities to reflect (the respective item achieved 3,90 points in average on the 5-point Likert scale; SD: 0,83). Further, according to the questionnaire results participants were able to collaborate (the related item achieved 4,70 points in average; SD: 0,56) and to get support from the trainer or peers (item achieved 4,90 points in average; SD: 0,30). The conducted frontal lecture showed instead considerable lower values compared to the learning factory treatments. Peer observation stated that the interplay of the physical learning factory elements and the virtual business game approach led to a better understanding for participants. Further, peer observations stated that the course following the learning factory principle starting with an initial non-agile state to a final optimized agile state had a positive effect on the course results. Participants mentioning that experiencing the difference of the non-agile state (exercise #1) and agile state (exercise #10) was the best aspect of the course confirms this statement.

The physical learning factory infrastructure

The above descript contributions of the developed and applied setting refer to the created learning environment. This includes besides the physical infrastructure of the learning factory other elements (e.g. learning objectives) and especially the above highlighted (virtual) extensions (see Table 69). Despite the previously mentioned fact that the physical learning factory forms the basis for the developed learning environment in total, the question arises: Is the physical infrastructure – the learning factory in the narrow sense – necessary? Or could other concepts such as e.g. serious games or purley digital learning settings substitute the physical infrastructure which is resource intensive to develop and operate (as described by Abele et al. 2019, p. 287). As the underlying premises of this doctoral thesis is that a learning factory is to be used for the intended competence development regarding the design of an agile operations system this question is not in the scope of this thesis. However, the applied research methodology and the collected data enables to highlight advantages of the physical learning factory concept in context to the overall goal of developing competences to design an agile operations system.

First, experiential learning environments are able to support (or hinder) the learning process (Borko and Putman 2009, p. 675). *Caine and Caine 1990* introduced 12 principles with the aim to increase the effect of learning environments (as described in section 2.3.3). In general, the developed training course and learning environment implements these principles (e.g. motivational, challenging and empowering, etc. - cf. Table 12, section 2.3.3). However, while different learning environments can as well adhere to these principles (e.g. serious games might as well provide a bigger contextual picture), the physical setting of the learning factory concept might be more advantageous with regard to some of these principles (indicated in bold in the following paragraphs).

Concerning the developed training course, this applies especially to the **involvement of different senses**. Based on *Caine and Caine 1990*, the actual hands-on tasks at the learning factory where all five senses are stimulated is expected to increase the learning process. The hands-on activities where highlighted by participants frequently as 'best aspect of the course' in the post-training questionnaire.

The learning factory exercises foster communication and collaboration among participants (the respective item achieved 4,70 points in average on the 5-point Likert scale; SD: 0,56 in the post-training questionnaire) and such **social activities increase learning** according to *Caine and Caine 1990*.

The principles further imply that **real-life projects increase understanding**. Hence, the abstracted close-to-reality learning factory setup and the task of participants to further develop this system throughout the training course is expected to increase theory understanding. The respective post-training questionnaire items addressing the contribution of concrete experiences to the overall learning process achieved 4.45 points in average on the 5-point Likert scale. (SD: 0,59)

Second, consulted literature in the research field of learning factories points out that learning factories support the development of relative context independent competences (Abele et al. 2019, p. 32 - see section 2.4.4) which contribute as well to the domain specific competence of designing an agile operations system. This includes socio-communicative competences such as the capability to work in teams and communication skills. As already stated above, the related item in the questionnaire showed that the physical learning factory setting provided participants the opportunity to collaborate throughout the training course (the respective item achieved 4,70 points in average on the 5-point Likert scale; SD: 0,56). Further, consulted literature points out that learning factories support the development of the personal competence ‘system thinking capabilities’. Peer and author observations show that especially actively working in the physical production system (including tasks such as e.g. assembling, inventory management, scheduling or capacity management) and thereby physical experienced implications of different disruptions and, in the further course, countermeasures to these disruptions, supported the understanding of the interconnected implications of an agile operations system. A participant replied when asked about the best aspect of the training course: *Exercises especially where we "ran the factory"*. Furthermore, literature states that the activity and action competence of ‘planning and realization capability’ is supported in learning factories. This context independent competence is addressed at the learning factory as the participants themselves carry out the design and the (physical) implementation of different agile operations elements. Several positive participants statements about the physical implementation of agile operations elements at the learning factory (such as *“Take lectures and implement the content in the learning factory right after”*) when asked about the best aspect of the training course support this conclusion.

As stated above, this research do not allow the comparison of different learning settings. However, from the point of view of the author of this thesis, the conducted research shows that the instrument ‘learning factory’ offers a strong combination of factors that support the intended competence development. Nevertheless, further research in this context is of interest and is addressed in the outlook of the present thesis at hand.

It can be concluded, that research question 2 was answered by the application of the developed training concept, the conducted quasi-experiment and data collection, analysis and synthesis (especially observations and results retrieved from the questionnaire instrument).

7.2 Discussion

This section argues about the quality of the conducted research study and its findings. This section discusses these four criteria of internal validity, external validity, reliability and objectivity in relation to the present research study.

7.2.1 Internal validity

Internal validity refers to the credibility of obtained results and data interpretation (Döring and Bortz 2016, p. 109). Techniques to ensure internal validity entail e.g. a comprehensive data acquisition, peer discussions or validation with investigated persons (Lincoln and Guba 1985, p. 301). In addition, *Döring and Bortz 2016* refer to *Schou et al. 2012* who propose a checklist consisting of seven points to maintain internal validity. In the following, this section outlines the measures of this research to achieve internal validity based on *Schou et al 2012* (indicated in bold).

The research **purpose** is clearly stated in chapter 3.1 along with the formulated research questions. The **research methodology** is outlined in chapter 4. This chapter further **argues why** this research study applies an action research approach and discusses the **methodological fit** between research questions, existing knowledge, intended research contributions and the chosen research approach. Concerning the data acquisition strategy, this research study characterized the applied **data collection methods** including the expected results and the time of data gathering (see section 4.4.2). Further, subsection 4.4.2 explained the followed approach to **data triangulation**. The **research process** is clearly stated and structured particularly according to the elaborated underlying research framework of the present study (see section 4.3). (based on Schou et al. 2012, p. 2090)

However, the author was actively involved as the trainer in conducted training actions as well as an observer (evaluation of intermediate training results) and was further responsible for data analysis and triangulation. Hence, the bias of the author due to e.g. previous experiences or personal interests might have affected the internal validity of this research study. Due to these shortcomings of the chosen action research approach, data collection methods followed a mixed methods approach including quantitative data (pre-post knowledge test and questionnaire) and peer observation. Further, the questionnaire gathered data from a participants' point of view adding a third perspective (peer observer, participants and author) on investigated actions. Above of that, the results and derived conclusions were partially published (see *Karre et al. 2018*, *Karre et al. 2019*) and discussed with experts. However, data was collected solely immediately after the conducted training actions. Thus, this research does not allow conclusions on long-term outcomes.

7.2.2 External validity

The external validity ensures that results and conclusions are generalizable to other contexts (Döring and Bortz 2016, p. 109). Therefore, consulted literature points out that a 'thick description' of the investigations (e.g. persons, boundary conditions) is necessary to be able to estimate the transferability to different persons and contexts (Lincoln and Guba 1985, p. 301). *Schou et al. 2012* propose five criteria (indicated in bold) to ensure external validity discussed in the following.

This research includes participants from masters programs in different fields of study. **Selection** and **argumentation** of included participants was outlined. However, accessibility to participants was a main limitation of this research study. The **participants were characterized** in detail for each conducted training action. Chapters 6.1 and 6.2 introduce the LEAD Factory and its specific **boundary conditions** ('context') as research environment. The **relationship** within this research study concerning the researcher (author of this thesis, employee at Graz University of Technology), peers (research personnel at Graz University of Technology, experienced in conducting training action at learning factories) and participants (mostly master program students) was made transparent. (based on Schou et al. 2012, p. 2090)

Naturally, the accessibility to participants affect the external validity of this research study. First, the previously mentioned dependency on personal-related and environmental confounding variables (see chapter 6.5) influence the transferability of results. Second, the fact that participants did not had substantially industry experiences has the potential to relativize results. To lessen the influence of personal-related confounding variables, the author conducted several training actions throughout two action research cycles. Further, all participants experienced a prior 2-day lean training to establish a common understanding of operations management. This research study was conducted at a single learning factory. Therefore, study results might not be representative for all learning factories. However, to enable a better transformability, this research outlines the general requirements and solution approaches independent from the actual application environment. Still, effort to transfer the developed training course elements to different settings is needed.

The lack of experienced industry personnel as investigative group limits the contribution (see section 8.1.3) and is addressed in the outlook of this research (see chapter 8.2).

7.2.3 Reliability

Reliability determines if research results would be achieved when the study is repeated in the same or a similar context (Döring and Bortz 2016, p. 109). Similar to previous research quality criteria, *Schou et al. 2012* propose six criteria (indicated in bold) to ensure reliability.

The retrieved data is **logical linked** to the research aims. The **process of data analysis** is described in section 4.4.2. **Study results** are introduced in detail throughout chapters 6.3 and 6.4. The detailed description of the results followed as well the underlying action research approach outlined in chapter 4.2. **Credibility** of findings is ensured by the mixed methods data collection approach. The results of the different data collection methods are made transparent and **support the interpretation**. Further, the results of the conducted study are **aligned** with the conclusions. (based on Schou et al. 2012, p. 2090).

Similar factors that concern the external validity (e.g. personal-related confounding variables of participants), might affect the reliability of this study. However, to ensure reliability, this research outlined the underlying research process and applied methods in detail (see chapter 4). Further, the present research strictly followed the described process. In addition, triangulation across different data gathering methods supports the reliability of the present research study.

7.2.4 Objectivity

The criteria of ‘objectivity’ (or neutrality) determines if research findings are driven by informants and the context of the inquiry and not by the researcher (e.g. bias, motivation) (Döring and Bortz 2016, p. 109). *Schou et al. 2012* propose as well for this criterion rules to follow (indicated in bold) in order to maintain objectivity discussed in the following.

Concerning this research, the **author** described his experiences and **background**. There are **references to existing knowledge** when applied. Throughout the present research study it is **clearly stated** when **results** were obtained from data (e.g. section 6.3.3) or solution approaches where formulated in advance (e.g. chapter 5.5). Further, following the outlined action research approach, the **role of the researcher** who conducted this study was described. (based on Schou et al. 2012, p. 2090)

The role of the researcher within the action research approach limits objectivity as researchers take actions (see chapter 4). Therefore, similar to previously mentioned concerns regarding internal validity, the researchers’ bias (e.g. motivation, interest) might affect the objectivity of this research. However, the research process itself and retrieved data (peer observation protocols, pre-post knowledge tests, questionnaires and intermediate training result evaluation) was documented to ensure objectivity.

CHAPTER 8

Summary and Outlook

This final chapter first summarizes the present research study. Dedicated subsections summarize existing knowledge, research aims, the applied research methodology, the chosen validation approach and contributions as well as limitations of this research study to literature and practice. Second, this chapter outlines related further research needs.

8.1 Research summary

The following first subsection summarizes existing knowledge concerning agile operations, basics of competence development, experiential learning and learning factories. Further, it outlines the research aim and the main research questions of this research study. Then, the second subsection introduces the applied action based research approach and outlines conducted research steps. Finally, section 8.1.3 introduces the contributions and limitations to literature and practice.

8.1.1 Existing knowledge & research aims

In today's volatile business environment coping successfully with uncertainties in operations is a pre-requisite to gain a competitive advantage. The concept of '**agile operations**' offers the potential to deal with change and has become growing attention from industry, practitioners and academia. Based on existing literature, this research considers 'sensing' of change ('agility drivers') and 'responding' to it as the two main pillars of agile operations. Agile operations is a multidimensional approach including activities across corporate functions and is applicable in different industries. However, related activities are individual to each company. Further, the concept of agile operations includes cooperations across the whole value chain.

Analyzed literature points out that management training and education are key-factors to operations improvement approaches like lean or six sigma. Similarly, to design an agile operations system responsible personnel needs knowledge and skills. Applying knowledge and skills to cope with new situations is referred to as '**competence**'. The conducted literature study showed that there is no research addressing the issue of competence development concerning the design of an agile operations system.

To develop competences consulted literature points out that experiential learning show promising results in the context of operations management. Experiential learning activities comprise that participants are involved without preconceptions, gain experiences and derive concepts to solve problems based on lived experiences. Suitable learning environments support learning processes linking pure theoretical information with context. In the case of operations management so-called '**learning factories**' are successfully implemented to develop several related competences. Learning factories are close-to-reality abstractions of industrial value chain sections. Such a learning environment enables the alternation of understanding, cognition, application and reflection processes to enhance learning in domain specific contexts.

The research purpose of the present thesis is to develop a learning factory based training course to enable competence development concerning the design of an agile operations system to cope with uncertainties in operation. Two main research questions were formulated. The first research question aimed to characterize factors of the learning environment. This first research question requires the formulation of respective (sub-)competences and the derivation of requirements of the subject matter agile operations on the learning environment. The second main research question aims to discuss elements of such a learning factory based setting supporting the competence development regarding an agile operations system.

RQ 1: What characterizes a learning factory based training concept that supports competence development regarding the design of an agile operations system?

RQ2: How does the concept 'learning factory' support competence development regarding the design of an agile operations system?

8.1.2 Research methodology and validation approach

The author chose to apply an action research approach. This primary form of empirical inquiry consists of a cyclical process. This process emphasizes research activities and taking actions in parallel. The methodological fit between the formulated research questions, the existing knowledge, the intended contributions of this research study and the action research approach is discussed in chapter 4.2. Further, chapter 4.2 describes considerations concerning maintaining the quality of the applied research approach (rigor, reflection and relevance) in relation to the present research study at hand.

The author elaborated a conceptual research framework depicting the model of what the present research study investigates. Further, this research framework formed the basis for the structured data collection and analysis approach. The empirical inquiry consists of two action research cycles of constructing and planning action, taking action and data acquisition, and the subsequent evaluation of taken actions. 'Actions' in this context refer to conducted training courses throughout this research study.

To develop the learning factory based training course the author chose to apply the guiding framework proposed by *Tisch 2018* based on the conducted literature study (see chapter 2.5). Consulted literature points out that competence formulation forms the basis for the development of training courses. Subsequently, this research work broke down the defined main competence into sub-competences, observable actions and knowledge elements. The knowledge elements relevant to the concept of agile operations were identified in a structured literature review (see chapter 5.2).

The developed training actions were conducted at Graz University of Technology's LEAD Factory. Four trainings with a total of 50 participants contributed to this research study. Further, a quasi-experiment was conducted to get insights into differences between a frontal lecture and the experiential learning factory treatment.

The applied data collection approach used a combination of qualitative and quantitative data. A written pre-post knowledge test based on derived learning objectives (knowledge elements of formulated sub-competences) was applied to assess the learning of participants. Peer observation and subjective author assessments throughout the taken actions provided the data basis to evaluate participants' reaction and to observe intermediate course results. In combination with the pre-post test results, the observation of participants' actions enabled a conclusion concerning the application of gained knowledge in new situations and therefore an assessment of the intended competence development. Further, a post training questionnaire consisting of proven items to assess especially the 'fit' of the learning environment and the subject matter of agile operations from a participants' point of view was used. The conducted quasi-experiment was evaluated based on the pre-post knowledge test and the questionnaire instrument.

Obtained data was analyzed within each research cycle. Taken actions of the first research cycle aimed to test and further develop the elaborated training course. Therefore, data sources were analyzed individually. Then, results of the different data sets were triangulated to identify needs for action subsequently addressed in research cycle two. The second research cycle aimed to implement and test targeted developments to the training course based on action research cycle one. Data analysis was performed correspondingly to the first research cycle. Finally, data obtained from the learning factory training actions was additionally analyzed across research cycles to discuss the underlying research questions. Furthermore, results of the quasi-experiment comparing the learning factory treatment with the frontal lecture teaching method were included to the analysis. Section 7.2 discusses the quality of the present research study.

8.1.3 Research results, contributions and limitations

Chapter 7 answered the research questions and discussed the main findings of the research study at hand. On the basis of formulated (sub-)competences and therefrom derived requirements to the learning environment the intended training course was developed. The developed training course was tested and further developed at a learning factory according to the applied research approach. The author answered research question 1 based on the obtained findings and concluded that three main characteristics (authentic problem situation, alternation of thinking and doing, opportunities to reflect) of a learning factory based training concept to develop the competence to design an agile operations system exist. The second research question is discussed based on conducted training courses and the quasi-experiment comparing the learning factory treatment with a lecture treatment measuring knowledge transfer and participants' reactions. Despite identified limitations of learning factories concerning the scope of the topic of agile operations, the author concluded on main learning factory contributions to the identified characteristics of the developed training course.

The following enumeration summarizes the answers to the research questions (characteristics and contributions of the learning factory setting - for more details see section 7.1).

- **Authentic problem situation:**
  - Enabling a high perception of problem importance
  - Providing stimulating and challenging learning situations
- **Alternation of thinking and doing:**
  - Bridging the gap between subject matter and exercises supporting the learning activities
  - Enabling participants' learning by made experiences
- **Opportunities to reflect:**
  - Providing opportunities to reflect on taken actions
  - Supporting collaboration among participants and trainer

Overall, the author concludes that the alignment between the learning factory as learning environment, applied teaching methods and used media show the necessary 'fit' with the subject matter of agile operations for successful competence development.

Further, the obtained results contribute to literature and practice. As outlined in the interim conclusion on the existing knowledge (see section 2.6), to the best knowledge of the author, the developed approach is the first published research work in its context.

The gained results of this research study extend current literature regarding agile operations. Consulted literature points out that scholars discuss especially strategies and tools of agile operations focusing more on *what* an agile operations system should contain than on *how* to develop such a system (see e.g. Sherehiy et al. 2007, p. 448). In contrast, this research study formulated necessary concrete sub-competences to design an agile operations system based on identified knowledge elements in literature. Despite the suggestion of the author that these sub-competences require further validation (through e.g. a large-scale quantitative inquiry on industry practice or a case study/clinical research study), the identified elements represent a necessary basis. Further, consulted literature about operations improvement programs and agile operations highlight the impact of training and education on their implementation success (see section 2.2.7). The developed and tested training course thus extends related literature and it is hoped that this research contributes to the successful implementation of agile operations in industrial practice. Limitations of this study in this respect are especially the investigative groups (students) and the solely focus on the first two levels of the 'four level model of training criteria' (see e.g. *Kirkpatrick and Kirkpatrick 2006*) neglecting the long-term impact on participants and organizations (e.g. measurement of participants change in behavior due to the training course and corporate results enabled through the attended training course).

This research study provides several contributions to existing knowledge concerning the research field of learning factories and their current practice. First, the research study at hand introduced a new topic to the learning factory community and showed in the conducted study at the LEAD Factory that the learning factory principle supports related competence development. To depict the topic of agile operations at a learning factory required covering a volatile world with uncertainties influencing operations at the learning factory and corresponding countermeasures leveraging the learning factory related value chain. These requirements interfered with stated limitations of learning factories in literature (see section 2.4.5 and chapter 5.3). Therefore, the author combined a fictional case study, a role-play, a monitoring system fitting to the learning factory principle and a business game with the 'classic' learning factory concept. To the author, especially the developed and tested integration of the business game in learning factory exercises contributes to literature related to the combination of virtual and physical learning factory elements ('hybrid learning factories'). Further, the developed monitoring system, which is an easy to implement tool for other learning factories, extends current practice.

Second, this research study developed the agile operations training course based on the proposed guiding framework by *Tisch 2018* despite its original limitation to the topic of lean production. Subsequently, the present research study confirmed that this guiding framework is well applicable to the subject matter of agile operations.

Third, this research study followed strictly the applied action research approach. The author studied in the course of the thesis at hand several research studies in the context of learning factories. To the best knowledge of the author, this research work is the first to apply such an action research approach in this context. The application of the action research approach with its parallel activities regarding 'taking action' and 'research' contributed extensively to the results of this work. It is hoped that this research study encourages scholars to apply an action based research approach in the context of future learning factory studies.

However, as discussed in chapter 7.2, described contributions to learning factory literature and practice might be limited as the developed approach was applied solely at a single learning factory with specific boundary conditions.

8.2 Outlook

This research work emphasized competence development regarding the design of an agile operations system in a learning factory based setting.

The underlying (sub-)competences were formulated based on current literature. As previously described, these competences should be further investigated. Therefore, it would be of interest to conduct e.g. large-scale quantitative industry surveys or case/clinical research in industry to deepen and extent the outlined competences. This would contribute to agile operations literature and practice as existing literature focus more on tools to enable agile operations than on how to implement it. Further research could address outlined limitations regarding time and accessibility (e.g. learning factory, participants) of this study.

First, the developed elements were applied solely at one learning factory with specific boundary conditions. Therefore, it would be of interest to apply the resulted training course at other learning factories. It is assumed that especially the lack of actual production machines limits the application of the studied subject and would further contribute to the mapping of the entire subject scope. This includes e.g. emphasizing the potential impact (physical - at the learning factory) of new production technologies on operations.

Second, this research work applied two action research cycles to test and further develop the resulting training course with the inclusion in total 50 participants. Still, it is beliefed that the inclusion of more participants would contribute to obtained research results. Especially the inclusion of industrial employees with practical experiences is expected to contribute to the further development of the presented research study results.

Third, this research does solely include the evaluation of participants' immediate reactions and their improvements concerning knowledge and competences. These evaluation criteria represent the first two levels of the 'four level model of training criteria' (see e.g. *Kirkpatrick and Kirkpatrick 2006*). The third (participants change in behavior), and the fourth level (results made possible due to the attended training) would be interesting to investigate. Such a research would request a long-term empirical study accompanying the design, implementation and operations phase ('results') of an agile operations system enabled by a learning factory supported competence development program. Besides the evaluation of the agile operations training course, such a research study would contribute to both research fields of agile operations and learning factories.

This thesis extended the 'classic' learning factory setting by a fictional case study representing a volatile business environment and an agile operations business game to enable especially the inclusion of more far-reaching measures across the value chain. Further, the agile operations business game served as 'fast-forward' mechanism to overcome time-related limitations of learning factories. To the author, especially the combination of these two elements could contribute to map further topics at learning factories related to e.g. supply chains, production networks or operations strategy. However, the present research study solely investigated competence-development directly at the learning factory. Therefore, it would be of interest to research a combination of remote and on-site teaching elements. Furthermore, the developed training course might be conducted purely in a virtual factory environment. From the author's point of view, such an approach has the potential to increase agile operations activities in industry.

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Appendix A: Learning Factory Morphology[20]

1. Operating model	1.1 Operator	Academic institution	Non-Academic institution	Profit oriented operator												
		University	College	BA	Vocational school/high school	Chamber	Union	Employer association	Industrial network	Consulting	Producing company					
	1.2 Trainer	Professor	Researcher	Student assistant	Technical expert/int. specialist	Consultant	Educationalist									
	1.3 Trainer	Own development	External assisted development	External development												
	1.4 Initial funding	Internal funds	Public funds	Company funds												
	1.5 Ongoing funding	Internal funds	Public funds	Company funds												
	1.6 Funding continuity	Short term funding (e.g., single events)	Mid-term funding (projects and programs <3 years)	Long-term funding (projects and programs >3 years)												
	1.7 Business model for trainings	Open models	Closed models (training program only for single company)													
		Club model	Course fees	BA												
2. Purpose and targets	2.1 Main purpose	Education	Vocational training	Research												
	2.2 Secondary purpose	Test environment/pilot environment	Industrial production	Innovation transfer	Advertisement for production											
	2.3 Target groups for education and training	Pupils	Students	Employees	Profit oriented operator											
			Bachelor	Master	PhD students	Apprentices	Skilled workers	Semi-skill. workers	Un-skilled workers	Lower mgmt	Middle mgmt	Top mgmt	Entrepreneurs	Freelancer	Unemployed	Open public
	2.4 Group constellation	Homogenous	Heterogeneous (knowledge level, hierarchy, students + employees, etc.)													
	2.5 Targeted industries	Mechanical & plant eng.	Automotive	Logistics	Transportation	FMCG	Aerospace									
		Chemical industry	Electronics	Construction	Insurance/banking	Textile industry	…									
	2.6 Subject-rel. learning contents	Prod. Mgmt & organization	Resource efficiency	Lean mgmt	Automation	CPPS	Work system design	HMI	Design	Intralogistics design & mgmt	…					
	2.7 Role of LF for research	Research object	Research enabler													
	2.8 Research topics	Production management & organization	Resource efficiency	Lean mgmt	Automation	CPPS	Changeability	HMI	Didactics	…						
3. Process	3.1 Product lifecycle	Product planning	Product development	Product design	Rapid prototyping	Manufacturing	Assembly	Logistics	Service	Recycling						
	3.2 Factory lifecycle	Investment planning	Factory concept	Process planning	Ramp-up				Maintenance	Recycling						
	3.3 Order lifecycle	Configuration & order	Order sequencing	Production planning and scheduling					Picking, packaging	Shipping						
	3.4 Technology lifecycle	Planning	Development	Virtual testing					Maintenance	Modernization						
	3.5 Indirect functions	SCM	Sales	Purchasing	HR	Finance/controlling	QM									
	3.6 Material flow	Continuous production	Discrete production													
	3.7 Process type	Mass production	Serial production	Small series production	One-off production											
	3.8 Manufacturing organization	Fixed-site manufacturing	Work-bench manufacturing	Workshop manufacturing	Flow production											
	3.9 Degree of automation	Manual	Partly automated/hybrid automation	Fully automated												
	3.10 Manufacturing methods	Cutting	Trad. primary shaping	Additive manufacturing	Forming	Joining	Coating	Change material properties								
	3.11 Manufacturing technology	Physical	Chemical	Biological												
4. Setting	4.1 Learning environment	Purely physical (planning + execution)	Physical LF supported by digital factory (see line "IT-integration")	Physical value stream of LF extended virtually	Purely virtual (planning + execution)											
	4.2 Environment scale	Scaled down	Life-size													
	4.3 Work system levels	Work place	Work system	Factory	Network											
	4.4 Enablers for changeability	Mobility	Modularity	Compatibility	Scalability	Universality										
	4.5 Changeability dimensions	Layout and logistics	Product features	Product design	Technology	Product quantities										
	4.6 IT-integration	IT before SOP (CAD, CAM, simulation)	IT after SOP (PPS, ERP, MES)	IT after production (CRM, PLM …)												
5. Product	5.1 Materiality	Material (physical product)	Immaterial (service)													
	5.2 Form of product	General cargo	Bulk cargo													
	5.3 Product origin	Own development	Development by participants	External development												
	5.4 Marketability of product	Available on the market	Available on the market but didactically simplified	Functional, could be available on the market	Without function/application, for demonstration only											
	5.5 No. of different products	1 product	2 products	3-4 products	>4 products	Flexible, developed by participants	Acceptance of real orders									
	5.6 No. of variants	1 variant	2-4 variants	4-20 variants	…	Flexible, depending on participants	Determined by real orders									
	5.7 No. of components	1 comp.	2-5 comp.	6-20 comp.	21-50 comp.	51-100 comp.	>100 comp.									
	5.8 Further product use	Re-use/re-cycling	Exhibition/display	Give-away	Sale	Disposal										
6. Didactics	6.1 Competence classes	Technical and methodological competencies	Social and communication competencies	Personal competencies	Activity and implementation oriented competencies											
	6.2 Dimensions learning targets	Cognitive	Affective	Psycho-motorical												
	6.3 Learn. scenario strategy	Instruction	Demonstration	Closed scenario	Open scenario											
	6.4 Type of learn. environment	Greenfield (development of factory environment)	Brownfield (improvement of existing factory environment)													
	6.5 Communication channel	Onsite learning (in the factory environment)	Remote connection (to the factory environment)													
	6.6 Degree of autonomy	Instructed	Self-guided/self-regulated	Self-determined/self-organized												
	6.7 Role of the trainer	Presenter	Moderator	Coach	Instructor											
	6.8 Type of training	Tutorial	Practical lab course	Seminar	Workshop	Project work										
	6.9 Standardization of trainings	Standardized trainings	Customized trainings													
	6.10 Theoretical foundation	Prerequisite	In advance (en bloc)	Alternating with practical parts	Based on demand	Afterwards										
	6.11 Evaluation levels	Feedback of participants	Learning of participants	Transfer to the real factory	Economic impact of trainings	Return on trainings/ROI										
	6.12 Learning success evaluation	Knowledge test (written)	Knowledge test (oral)	Written report	Oral presentation	Practical exam	None									
7. Metrics	7.1 No. of participants per training	1-5 participants	5-10 participants	10-15 participants	15-30 participants	>30 participants										
	7.2 No. of standardized trainings	1 training	2-4 trainings	5-10 trainings	>10 trainings											
	7.3 Aver. duration of a single training	<1 day	1-2 days	3-5 days	5-10 days	10-20 days	>20 days									
	7.4 Participants per year	<50 participants	50-200 participants	201-500 participants	501-1000 participants	>1000 participants										
	7.5 Capacity utilization	<10%	10-20%	21-50%	51-75%	76-100%										
	7.6 Size of LF	<100 sqm	100-300 sqm	300-500 sqm	500-1000 sqm	>1000 sqm										
	FTE in LF	<1	2-4	5-9	10-15	>15										

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[20] Abele et al. 2019, pp. 100–118

Appendix B: Data collection methods

Pre-post knowledge test

Field of study: ________________ Study progress:
0% 50% 100%
o-----------o------------o------------o-------------o

Q1: Name the three origin areas of uncertainties and give a short example for each area.

▶ ____

▶ ____

▶ ____

Q2: Name effects of uncertainties on operations (at least 4 out of 6).

▶ ____________________ ▶ ____________________

▶ ____________________ ▶ ____________________

▶ ____________________ ▶ ____________________

Q3 What are the three main monitoring functions.
What is the benefit of a monitoring system (make a sketch!)?

▶ ____________________

▶ ____________________

▶ ____________________

Q4: What are core elements of organizations when it comes to cope with (external) uncertainties

▶ ____________________ ▶ ____________________

▶ ____________________ ▶ ____________________

Q5: Name operation categories/areas of possible influencing parameters (operation levers) to cope with uncertainties in operations (at least 4 out of 6).

▶ ____________________ ▶ ____________________

▶ ____________________ ▶ ____________________

▶ ____________________ ▶ ____________________

Q6: What is the content of a “playbook”/”operations manual” and why is it important?

What	Why

Peer observation sheet[21]

Please rate following statements from “strongly agree” to “strongly disagree”.
Please enter further comments on where you see potential for improvement.

	Strongly agree	Agree	Neutral	Disagree	Strongly Disagree	additional comments
Experiments/exercises are well chosen and well organized.	○	○	○	○	○	
Experiments/exercises are important supplements to the course.	○	○	○	○	○	
Experiments are consistent with objectives	○	○	○	○	○	
Experiments/exercises develop important skills.	○	○	○	○	○	
Experiments/exercises are of appropriate length.	○	○	○	○	○	
Experiments/exercises are appropriately challenging	○	○	○	○	○	
Course learning objectives are clear and appropriate	○	○	○	○	○	
Lecture notes are well organized and clearly written.	○	○	○	○	○	
Supplementary handouts and web pages are well organized and written	○	○	○	○	○	
Student products demonstrate satisfaction of learning objectives	○	○	○	○	○	

What was the best aspect of the course?

____

____

____

What would you suggest to improve?

____

____

____

Is there anything else you would like to add?

____

____

____

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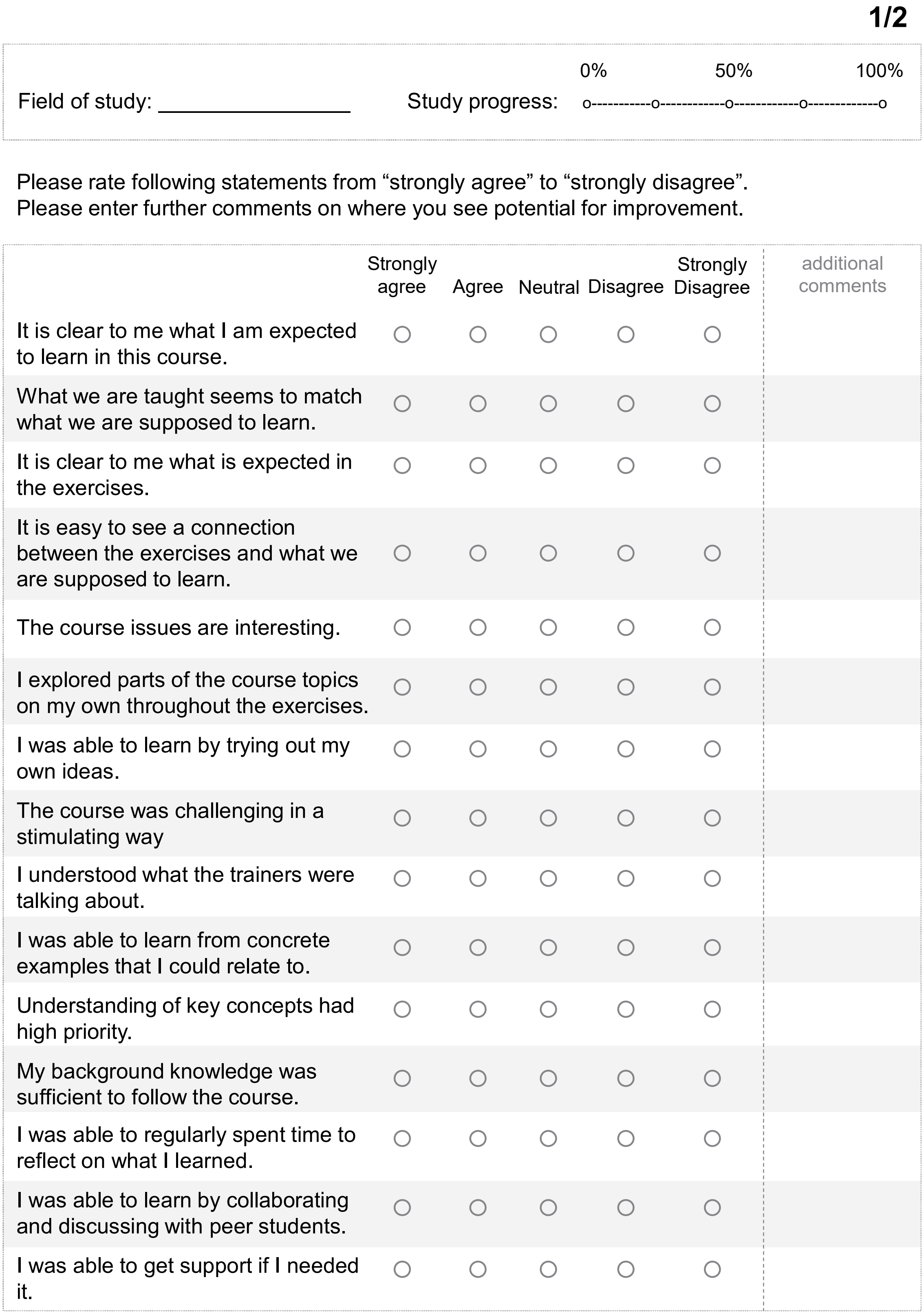
[21] *Centre for Teaching Support & Innovation 2017; Brent R. and Felder 2004*

Questionnaire[22]



1/2

Field of study: ________________

Study progress: 0% o-----------o------------ 50% o------------o------------- 100% o

Please rate following statements from “strongly agree” to “strongly disagree”.
Please enter further comments on where you see potential for improvement.

	Strongly agree	Agree	Neutral	Disagree	Strongly Disagree	additional comments
It is clear to me what I am expected to learn in this course.	○	○	○	○	○	
What we are taught seems to match what we are supposed to learn.	○	○	○	○	○	
It is clear to me what is expected in the exercises.	○	○	○	○	○	
It is easy to see a connection between the exercises and what we are supposed to learn.	○	○	○	○	○	
The course issues are interesting.	○	○	○	○	○	
I explored parts of the course topics on my own throughout the exercises.	○	○	○	○	○	
I was able to learn by trying out my own ideas.	○	○	○	○	○	
The course was challenging in a stimulating way	○	○	○	○	○	
I understood what the trainers were talking about.	○	○	○	○	○	
I was able to learn from concrete examples that I could relate to.	○	○	○	○	○	
Understanding of key concepts had high priority.	○	○	○	○	○	
My background knowledge was sufficient to follow the course.	○	○	○	○	○	
I was able to regularly spent time to reflect on what I learned.	○	○	○	○	○	
I was able to learn by collaborating and discussing with peer students.	○	○	○	○	○	
I was able to get support if I needed it.	○	○	○	○	○	

---

[22] *Herrmann et al. 2016; Borglund et al. 2016*

2/2

What was the best aspect of the course?

____

____

____

What would you suggest to improve?

____

____

____

Is there anything else you would like to add?

____

____

____

Appendix C: Learning situations[23]

Competence addressed

Sub-competence	Observable action	Profession knowledge	Conceptual knowledge
"Participants of the agile operations training are able to ***identify*** *and* ***structure*** *external and internal uncertainties on different business levels."*	- Participants experience uncertainties and their impact on operations (with different viewpoints – e.g. operations manager) - Participants identify possible uncertainties on different areas of origin for the learning factory embedded case using appropriate tools - Participants structure the identified uncertainties according to their characteristics (impact on operations)	- Types of uncertainties and related-basic terms - Origin areas of uncertainties - Application of tools to structure uncertainties on different origin areas (e.g. Ishikawa diagram, Porter's 5 Forces, PESTEL analysis)	- Different types of uncertainties influence the potential effect on operations and business - Classification of uncertainties within the business environment according to areas of origin is important for a systematic identification of uncertainties - Why understanding current developments of uncertainties is important for business success (increasing volatility, complex interrelationships, uncertain developments --> uncertainty as new normal)

Learning sequence in detail (Exercise #1)

Participants get familiar with introduced roles in groups (e.g. 2 participants per each role)

Participants get familiar with their workplace at the learning factory; Observers start observing;

Operations management "start" production(e.g. prepare Hejunka board, set takt time); operators start working

Purchasing management and general management start taking decisions to maintain production (e.g. reordering parts)

The trainer provides throughout the exercise different 'action cards' simulating uncertainties on different levels (e.g. political, supply chain)

Participants need to prepare for the potential impact(s) of the given uncertainties (e.g. switch suppliers).

When disruptions 'hit' operations, participants try to maintain production

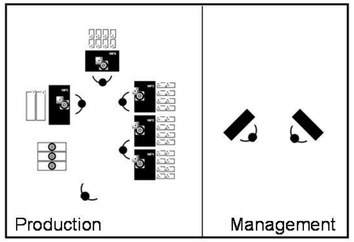
Observers report their findings; in a group discussion the trainer and participants elaborate a timeline with uncertainties (and impacts); participants discuss/identify different levels and characteristics of uncertainty

Trainer interference

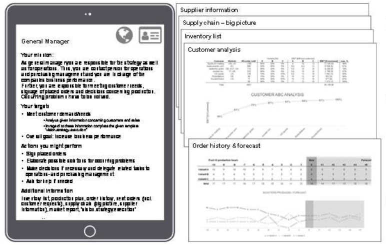
Participants action

Learning factory setup and information

Infrastructure

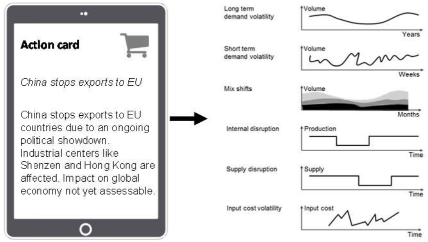


Participant information



- Predefined roles: operator, operations manager, purchasing manager, general manager
- Detailed specific information for each role (e.g. purchasing manager – inventory level, general manager – customer analysis,..)
- Each role is provided with possible actions to take and objectives to fulfill

Trainer material


Action card

China stops exports to EU

China stops exports to EU countries due to an ongoing political showdown. Industrial centers like Shenzen and Hong Kong are affected. Impact on global economy not yet assessable.

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[23] As proposed by e.g. Enke et al. 2016a, p. 10

Competence addressed

Sub-competence

"Participants of the agile operations training are able to ***analyze****,* ***define*** *and* ***select*** *requirements and sensors to early detect external and internal uncertainties."*

Observable action

- Participants discuss the impact of the experienced uncertainties
- Participants estimate the probability of occurrence, the response capability and the impact on the as-is state of the learning factory embedded case for the identified uncertainties
- Participants formulate negative as well as positive implications of uncertainties
- Participants derive a "probability impact matrix" to prioritize need for action

Profession knowledge

- Possible effects and characteristic of uncertainties on operations
- How to use the tool "Probability impact matrix" to define and visualize the need for action based on the possibility of occurrence and the impact of uncertainties on operations

Conceptual knowledge

- Understanding the characteristics and effects of uncertainties on operations is important in order to estimate the impact and to prepare counter measures
- Uncertainties entail risks but also opportunities for companies

Learning sequence in detail

Exercise #2

Participants structure the occurred disruptions of exercise #1 into 'levels of uncertainties' → Participants get familiar with the fictive company and the respective business environment (supply chain, customer structure etc.) → Participants identify possible uncertainties on different levels of origin using the tools Ishikawa diagram, Porter's 5 forces, and PESTEL analysis → Participants cluster identified uncertainties according to their effects on operations

Participants discuss their results in group discussions. Finally, the trainer and participants discuss the impact of selected disruptions on the fictive learning factory company and its value stream (supplier → customer) in detail

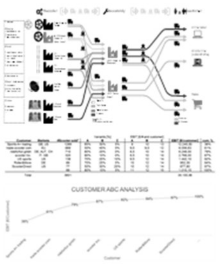
Exercise #3

Participants (in groups) discuss the impact of their identified uncertainties and resulting disruptions to the fictive company value stream (supplier → customer) → Participants formulate negative as well as positive implications of identified uncertainties ('scenarios') → Participants estimate the occurrence and the impact on the fictional learning factory company → Participants derive a probability impact matrix and discuss their resulting scenarios

Learning factory setup and information

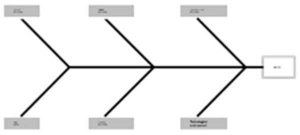
Fictive learning factory company Information

- Product information
- Production process information (additional to learning factory)
- Supplier structure, ratings, etc.
- Customer information (trends, ABC-Analysis, etc.)
- Etc.

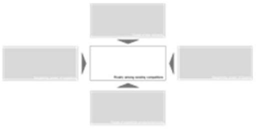


Exercise material

Ishiskawa diagram (company level)

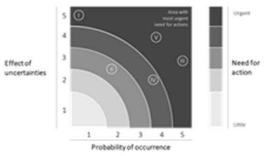


Porter's 5 Forces (micro level)



PESTEL Analysis (macro level)

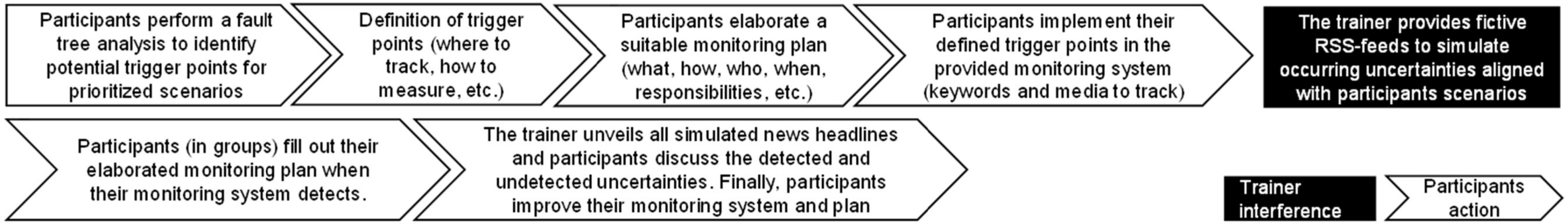
Probability impact matrix



Competence addressed

Sub-competence	Observable action	Profession knowledge	Conceptual knowledge
*"Participants of the agile operations training are able to **analyze**, **define** and **select** requirements and sensors to early detect external and internal uncertainties."*	- Participants set-up a working monitoring system based on qualitative information and define keywords- and keyword combination to effectively monitor top-5 rated uncertainties - Participants chose scope of monitoring based on identified and prioritized uncertainties - Participants elaborate a fault tree analysis for each origin areas of uncertainties to identify 'trigger points' - Participants define keywords and keyword combinations to monitor defined trigger points	- Different types of information and related types of sensors - Typical fields of monitoring and tools to derive systematically requirements and dependencies for sensors (fault tree analysis) - Define situation specific trigger points to select corresponding sensors	- Monitoring enables companies to early detect and fast react on uncertainties to thrive change
*"Participants of the agile operations training are able to **structure** and **generate** a monitoring report for decision makers to early react on uncertainties."*	- Participants elaborate a monitoring plan defining e.g. baseline, trigger point level (upper/lower limit), frequency of measurements, responsible person for monitoring, and the reporting process - Participants implement the generated monitoring system at the learning factory and analyze in a learning factory exercise gathered information - Participants experience and discuss the impact on the learning factory role play (to-be state)	- Basic elements of a monitoring plan in order to process gathered information by a monitoring system - How to structure retrieved information	- Monitoring needs to be strongly aligned with governance & control and agile operations levers to best support the agile operations concept

Learning sequence in detail (Exercise #4)



Participants perform a fault tree analysis to identify potential trigger points for prioritized scenarios

Definition of trigger points (where to track, how to measure, etc.)

Participants elaborate a suitable monitoring plan (what, how, who, when, responsibilities, etc.)

Participants implement their defined trigger points in the provided monitoring system (keywords and media to track)

The trainer provides fictive RSS-feeds to simulate occurring uncertainties aligned with participants scenarios

Participants (in groups) fill out their elaborated monitoring plan when their monitoring system detects.

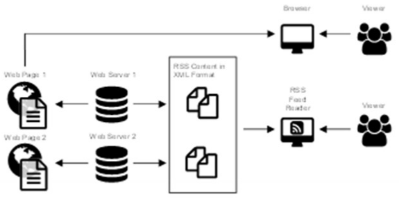
The trainer unveils all simulated news headlines and participants discuss the detected and undetected uncertainties. Finally, participants improve their monitoring system and plan

Trainer interference

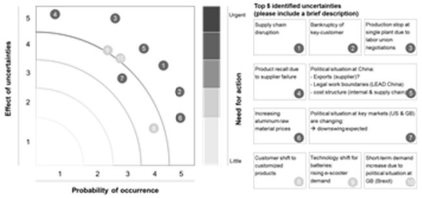
Participants action

Learning factory setup and information

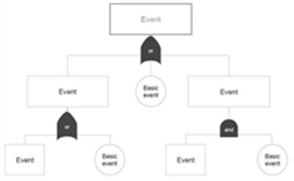
Infrastructure
Monitoring system



Participant information
Resulting (exercise #3) probability impact matrix and underlying scenarios



Trainer material
Exemplary Fault Tree Analysis



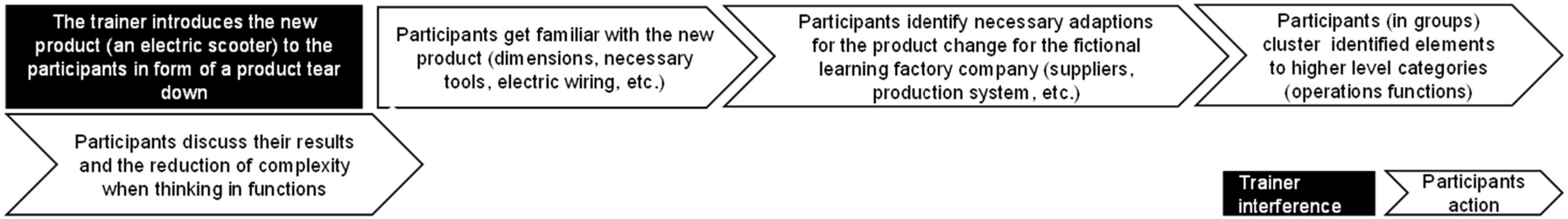
Monitoring plan

```
<item>
<title>
Ship incident forces oil
catastrophe near china
</title>
<pubdate>
Friday, 5 March 2020
</pubdate>
<description>
Update on environmental crisis on
the coast of china, Hong Kong.
Still supply chains to europe
and US are disrupted.
Delivery delays for europe
expected.
</description>
</item>
```

Competence addressed

Sub-competence	Observable action	Profession knowledge	Conceptual knowledge
"Participants of the agile operations training are able to ***assess*** *current operations regarding agility."*	- Participants elaborate appropriate categories to assess agility in the current operations via implementing a new, different product into the existing factory environment - Participants assess the as-is state of the learning factory embedded case (including the whole value chain) with the agility index in order to figure out how good the as-is state can cope with uncertainties	- Higher level operations categories to cluster agile operations adjusting levers - How to use the agility index as assessment tool for the whole value network	- Agile operations assessment is necessary to understand the gaps and improvement needs - Operations can be clustered into fields of actions for adjusting levers to systematic improve agile operations)

Learning sequence in detail (Exercise #5)



The trainer introduces the new product (an electric scooter) to the participants in form of a product tear down

Participants get familiar with the new product (dimensions, necessary tools, electric wiring, etc.)

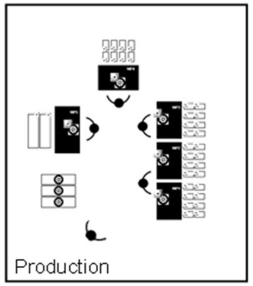
Participants identify necessary adaptions for the product change for the fictional learning factory company (suppliers, production system, etc.)

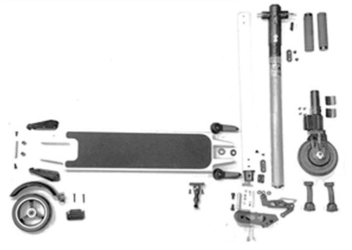
Participants (in groups) cluster identified elements to higher level categories (operations functions)

Participants discuss their results and the reduction of complexity when thinking in functions

Learning factory setup and information

Infrastructure





New product

Competence addressed

Sub-competence	Observable action	Profession knowledge	Conceptual knowledge
"Participants of the agile operations training are able to **define** and **create** the appropriate agility need level for operations."	- Participants familiarize themselves with strategic targets of the learning factory embedded case as basis - Participants define targets concerning agile operations for each agile operations lever category based on strategic targets of the embedded learning factory case - Participants generate concrete levers to improve agility, estimate the impact on operations of each lever and elaborate dependencies of lever combinations - Participants formulate 2 scenarios based on identified uncertainties and discuss different lever combinations to better cope with the uncertainties - Participants chose in the agile operations business game concrete levers for the learning factory embedded case and its degree of implementation - Participants experience and discuss the impact of the chosen levers on operations	- Requirements of future strategic work – examples of agile operations levers - How to appropriate formulate agile operations levers (necessary details) - Characteristics of possible levers concerning implementation cost vs. implications on operations - Tool "Design Structure Matrix" to map dependencies of different levers - Basics of scenario-planning	- Classic strategic work is changing - Agile operations levers need to be aligned with the corporate strategy - Pro-activity needs the formulation of scenarios and the preparation of agile operation levers - Different agile operation lever combinations have different implications on each lever, its effects and subsequently on the operations function

Learning sequence in detail

Exercise #6
- The trainer provides Trainer introduces the "agility index" to assess production systems
- Participants (in groups) rate the current setup of the learning factory (and surrounding case) based experiences from previous exercises
- Participants present and discuss their ratings

Exercise #7
- The trainer introduces concrete examples of agile operations levers for the different operations functions
- Participants identify possible agile operations levers for the fictional company (production system, supply chain, etc.)
- Participants use a design-structure-matrix to show interdependencies among the identified agile operations levers
- Participants choose two previous identified scenarios and 'apply' identified discuss an appropriate combinations of their levers to counteract scenario implications
- Participants present and discuss their results

Exercise #8
- Participants get familiar with the provided operations strategy of the fictional learning factory company (Ansoff Matrix)
- Combination of future operations strategy and previous identified uncertainties (scenarios)
- Derivation of an appropriate (future strategy vs. company situation) agility level for operations functions
- Definition of appropriate agile operations levers in the agile operations business game to achieve the indented agility level
- Reasoning and discussion of resulting agile operations levers

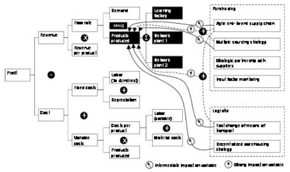
Trainer interference

Participants action

Learning factory setup and information

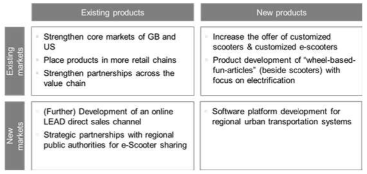
Infrastructure

Agile operations business game



Participant information

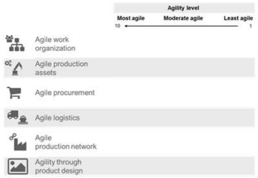
Ansoff-Matrix for future strategic directions



	Existing products	New products
Existing markets	Strengthen core markets of GB and US Place products in more retail chains Strengthen partnerships across the value chain	Increase the offer of customized scooters & customized e-scooters Product development of "wheel-based-fun-articles" (beside scooters) with focus on electrification
New markets	(Further) Development of an online LEAD direct sales channel Strategic partnerships with regional public authorities for e-Scooter sharing	Software platform development for regional urban transportation systems

Trainer material

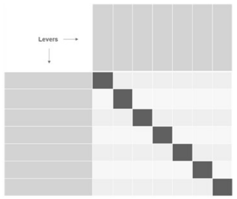
Agility index



Scenarios

	Brief description of scenario I (What happens?)	Impact on operations	Levers & Lever combinations to cope with scenario I
Scenario I: „Upswing"			
Scenario II: „Downswing"			

Design-structure-matrix



Competence addressed

Sub-competence	Observable action	Profession knowledge	Conceptual knowledge
"Participants of the agile operations training are able to ***analyze*** *and* ***define*** *roles and responsibilities in a corporate agility system relevant to operations."*	- Participants analyze the as-is state concerning roles and responsibilities and define a new organizational structure for the learning factory embedded case (incl. role descriptions, responsibilities etc.) - Participants elaborate an agility playbook for operations - Participants implement their organizational structure and their playbook at the learning factory (to-be state) and experience and discuss its impact	- Necessary content of an agility playbook - Organizational structures that support the concept of agile operations - Main corporate functions that influence a corporate agility system - Responsibilities and necessary (well defined) intersection to run the corporate agility system	- People, structure and processes are important for the concept of agile operations - Awareness for change and the necessity of the empowerment of employees is important - The concept of agile operations needs broad collaboration across different company functions
"Participants of the agile operations training are familiar with an appropriate performance management for the concept of agile operations."	- Participants experience the to-be state with the chosen agile operations levers and the developed roles and responsibilities at the learning factory - Participants discuss based on a qualitative scorecard performance management approach the impact of the elaborated improvements throughout the course.	- Performance management approach across different company levels - Scorecard dimensions to track agile operations activities	- Track agile operations activities is needed in order to continuously further improve the overall system - Governance structure is needed to coordinate agility as cross-functional approach

Learning sequence in detail

Exercise #9

- Recap of organizational structure in exercise #1 (role play)
- Participants (in groups) define new roles and responsibilities for the agile-state of the fictional learning factory company
- Participants derive an operations playbook defining e.g. responsibilities, potential agile operations levers (chosen in the agile operations business game), etc. based on derived scenarios
- Participants present their derived responsibilities and playbooks

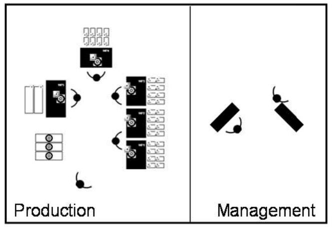
Exercise #10

- Participants get familiar with their roles (derived in previous exercise)
- Operations management "start" production(e.g. prepare Hejunka board, set takt time); operators start working
- Purchasing management and general management start taking decisions to maintain production (e.g. reordering parts)
- Monitoring system is working (as improved in exercise #4)
- The trainer provides throughout the exercise fictive RSS-feeds to simulate occurring uncertainties
- Participants need to use the derived agile operations system (chosen levers – physical, playbook, etc.) to counteract impact(s) of the given uncertainties (e.g. switch suppliers).
- In a debriefing session after the physical learning factory experience, the trainer introduce round-by-round the achieved virtual results of the chosen agile operations levers in the agile operations business game
- Observers report their findings; in a group discussion the trainer and participants discuss the impact of the agile operations system (physical, organizational structure, agile operations business game, etc.)

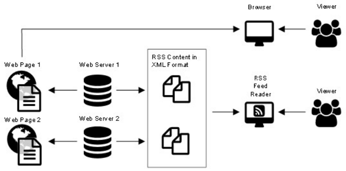
■ Trainer interference
▷ Participants action

Learning factory setup and information

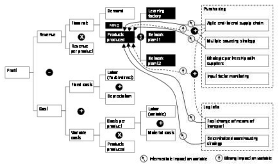
Infrastructure
Physical learning factory



Monitoring system



Agile operations business game



Trainer material
Simulated news (in XML format)

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<item>
<title>
Ship incident forces oil
catastrophe near china
</title>
<pubdate>
Friday, 5 March 2020
</pubdate>
<description>
Update on environmental crisis on
the coast of china, Hong Kong.
Still supply chains to europe
and US are disrupted.
Delivery delays for europe
expected.
</description>
</item>
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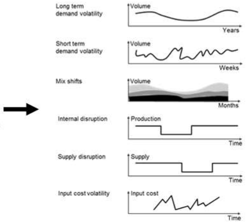


Appendix D: Competence matrix “design an agile operations system”

Table 70: Competence matrix ‘uncertainty’

Module	Sub-competence	Observable action	Professional knowledge (‘what’, ‘when’, ‘how’)	Conceptual knowledge (‘why’)	Considered research (knowledge lements)
Uncertainty	Participants of the agile operations training are able to **identify** and **structure** external and internal uncertainties on different business levels.	- Participants experience uncertainties and their impact on operations (with different viewpoints – e.g. operations manager) - Participants identify possible uncertainties on different areas of origin for the learning factory embedded case using appropriate tools - Participants structure the identified uncertainties according to their characteristics (impact on operations)	- Types of uncertainties and related basic terms - Origin areas of uncertainties - Application of tools to structure uncertainties on different origin areas (e.g. Ishikawa diagram, Porter’s 5 Forces, PESTEL analysis)	- Different types of uncertainties influence the potential effect on operations and business - Classification of uncertainties within the business environment according to areas of origin is important for a systematic identification of uncertainties - Why understanding current developments of uncertainties is important for business success (increasing volatility, complex interrelationships, uncertain developments --> uncertainty as new normal)	*Ramsauer et al. 2017*; *Ramesh and Devadasan 2007*; *Irfan et al. 2019*; *Christopher et al. 2004*; *Kleindorfer and Saad 2005*; *Zhang and Sharifi 2000*; *Shan et al. 2013*; *Grøtan and Paltrinieri 2016*; *Sahebjamnia et al. 2018*; *Cheese 2016*
	Participants of the agile operations training are able to **analyze** and **prioritize** the impact of identified uncertainties on operations according to the need for action.	- Participants discuss the impact of the experienced uncertainties - Participants estimate the probability of occurrence, the response capability and the impact on the as-is state of the learning factory embedded case for the identified uncertainties - Participants formulate negative as well as positive implications of uncertainties - Participants derive a "probability impact matrix" to prioritize need for action	- Possible effects and characteristic of uncertainties on operations - How to use the tool "Probability impact matrix" to define and visualize the need for action based on the possibility of occurrence and the impact of uncertainties on operations	- Understanding the characteristics and effects of uncertainties on operations is important in order to estimate the impact and to prepare counter measures. - Uncertainties entail risks but also opportunities for companies	*Ramsauer et al. 2017*; *Ramesh and Devadasan 2007*; *Kleindorfer and Saad 2005*; *Zhang and Sharifi 2000*; *Sahebjamnia et al. 2018*; *Cheese 2016*; *Hamad and Yozgat 2017*; *Vagnoni and Khoddami 2016*; *Vecchiato 2015*; *Teece 2007*; *Yang and Liu 2012*; *Wilson 2004*; *Paek and Lee 2018*

Table 71: Competence matrix ‘monitoring’

Module	Sub-competence	Observable action	Professional knowledge (‘what’, ‘when’, ‘how’)	Conceptual knowledge (‘why’)	Considered research (knowledge elements)
Monitoring	Participants of the agile operations training are able to **analyze**, **define** and **select** requirements and sensors to early detect external and internal uncertainties.	- Participants set-up a working monitoring system based on qualitative information and define keywords- and keyword combination to effectively monitor top-5 rated uncertainties - Participants chose scope of monitoring based on identified and prioritized uncertainties - Participants elaborate a fault tree analysis for each origin areas of uncertainties to identify ‘trigger points’ - Participants define keywords and keyword combinations to monitor defined trigger points	- Different types of information and related types of sensors - Typical fields of monitoring and tools to derive systematically requirements and dependencies for sensors (fault tree analysis) - Define situation specific trigger points to select corresponding sensors	- Monitoring enables companies to early detect and fast react on uncertainties to thrive change	*Ramsauer et al. 2017*; *Ramesh and Devadasan 2007*; *Irfan et al. 2019*; *Christopher et al. 2004*; *Kleindorfer and Saad 2005*; *Shan et al. 2013*; *Grøtan and Paltrinieri 2016*; *Hamad and Yozgat 2017 Vagnoni and Khoddami 2016; Vecchiato 2015; Wilson 2004; Vokurka and Fliedner 1998; Al Haderi 2019; Sambamurthy et al. 2003; Nejatian et al. 2018; Arbussa et al. 2017; Teece 2007; Braunscheidel and Suresh 2009; Yang and Liu 2012; Dervitsiotis 2004; Paek and Lee 2018; Arias and Solana 2013; Yusof and Aziz 2008*
	Participants of the agile operations training are able to **structure** and **generate** a monitoring report for decision makers to early react on uncertainties.	- Participants elaborate a monitoring plan defining e.g. baseline, trigger point level (upper/lower limit), frequency of measurements, responsible person for monitoring, and the reporting process - Participants implement the generated monitoring system at the learning factory and analyze in a learning factory exercise gathered information - Participants experience and discuss the impact on the learning factory role play (to-be state)	- Basic elements of a monitoring plan in order to process gathered information by a monitoring system - How to structure retrieved information	- Monitoring needs to be strongly aligned with governance & control and agile operations levers to best support the agile operations concept	*Ramsauer et al. 2017*; *Ramesh and Devadasan 2007*; *Christopher et al. 2004*; *(Kleindorfer and Saad 2005; Shan et al. 2013; Vagnoni and Khoddami 2016; Vecchiato 2015; Teece 2007; Wilson 2004; Vokurka and Fliedner 1998; Al Haderi 2019; Sambamurthy et al. 2003; Braunscheidel and Suresh 2009; Yusof and Aziz 2008; Arias and Solana 2013; Wang et al. 2012)*

Appendix D: Competence matrix “design an agile operations system”

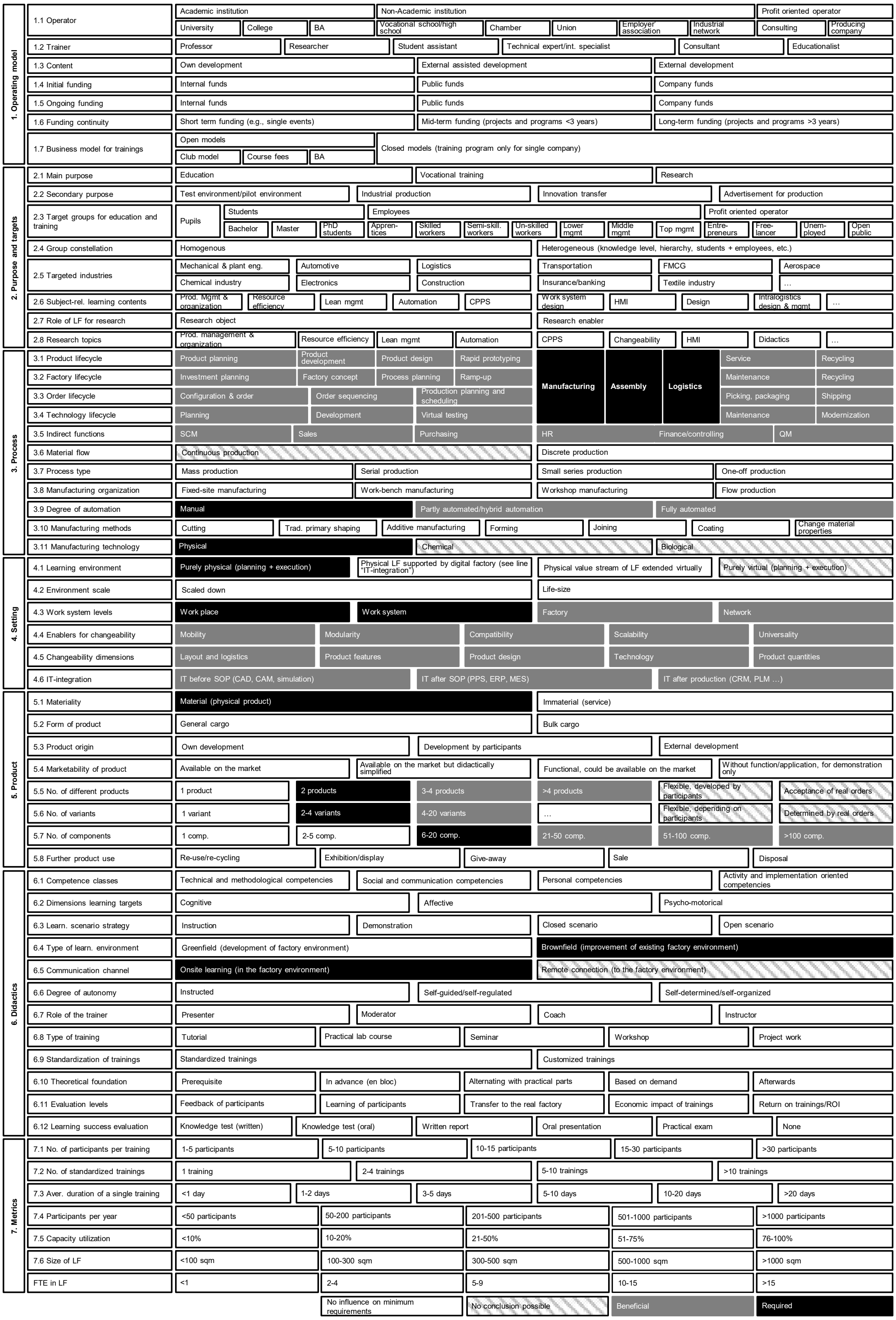
Table 72: Competence matrix ‘strategic alignment’

Module	Sub-competence	Observable action	Professional knowledge (‘what’, ‘when’, ‘how’)	Conceptual knowledge (‘why’)	Considered research (knowledge elements)
Strategic alignment	Participants of the agile operations training are able to **assess** current operations regarding agility.	- Participants elaborate appropriate categories to assess agility in the current operations via implementing a new, different product into the existing factory environment - Participants assess the as-is state of the learning factory embedded case (including the whole value chain) with the agility index in order to figure out how good the as-is state can cope with uncertainties	- Higher level operations categories to cluster agile operations adjusting levers - How to use the agility index as assessment tool for the whole value network	- Agile operations assessment is necessary to understand the gaps and improvement needs - Operations can be clustered into fields of actions for adjusting levers to systematic improve agile operations	*Ramsauer et al. 2017; Zhang and Sharifi 2000; Vokurka and Fliedner 1998; Nejatian et al. 2018; Arbussa et al. 2017; Tiwari and Tiwari J.K. 2019; Swafford et al. 2006a; Doz and Kosonen 2008; L'Hermitte et al. 2016; Ferdows and Thurnheer 2011; Jin-Hai et al. 2003*
	Participants of the agile operations training are able to **define** and **create** the appropriate agility need level for operations.	- Participants familiarize themselves with strategic targets of the learning factory embedded case as basis - Participants define targets concerning agile operations for each agile operations lever category based on strategic targets of the embedded learning factory case - Participants generate concrete lIntroevers to improve agility, estimate the impact on operations of each lever and elaborate dependencies of lever combinations - Participants formulate 2 scenarios based on identified uncertainties and discuss different lever combinations to better cope with the uncertainties - Participants chose in the agile operations business game concrete levers for the learning factory embedded case and its degree of implementation - Participants experience and discuss the impact of the chosen levers on operations	- Requirements of future strategic work - examples of agile operations levers - How to appropriate formulate agile operations levers (necessary details) - Characteristics of possible levers concerning implementation cost vs. Implications on operations - Tool "Design Structure Matrix" to map dependencies of different levers - Basics of scenario-planning	- Classic strategic work is changing - Agile operations levers need to be aligned with the corporate strategy - Pro-activity needs the formulation of scenarios and the preparation of agile operation levers - Different agile operation lever combinations have different implications on each lever, its effects and subsequently on the operations function	*Ramsauer et al. 2017; Vagnoni and Khoddami 2016; Teece 2007; Wilson 2004; Braunscheidel and Suresh 2009; Yusof and Aziz 2008; Tiwari R.K and Tiwari J.K. 2019; Swafford et al. 2006a, 2006b; Doz and Kosonen 2008; L'Hermitte et al. 2016; Martinez-Sanchez et al. 2019; Wadhwa et al. 2007; Ren et al. 2003; Kangilaski and Shevtshenko 2017; Angwin et al. 2009; Brown and Bessant 2003; Shimizu and Hitt 2004*

Table 73: Competence matrix ‘governance’

Module	Sub-competence	Observable action	Professional knowledge (‘what’, ‘when’, ‘how’)	Conceptual knowledge (‘why’)	Considered research (knowledge elements)
Governance	Participants of the agile operations training are able to **analyze** and **define** roles and responsibilities in a corporate agility system relevant to operations.	- Participants analyze the as-is state concerning roles and responsibilities and define a new organizational structure for the learning factory embedded case (incl. role descriptions, responsibilities etc.) - Participants elaborate an agility playbook for operations - Participants implement their organizational structure and their playbook at the learning factory (to-be state) and experience and discuss its impact	- Necessary content of an agility playbook - Organizational structures that support the concept of agile operations - Main corporate functions that influence a corporate agility system - Responsibilities and necessary (well defined) intersection to run the corporate agility system	- People, structure and processes are important for the concept of agile operations - Awareness for change and the necessity of the empowerment of employees is important - The concept of agile operations needs broad collaboration across different company functions	*Ramsauer et al. 2017; Ramesh and Devadasan 2007; Christopher et al. 2004; Hamad and Yozgat 2017; Vagnoni and Khoddami 2016; Teece 2007; Vokurka and Fliedner 1998; Sambamurthy et al. 2003; Braunscheidel and Suresh 2009; Dervitsiotis 2004; Doz and Kosonen 2008; L'Hermitte et al. 2016; Jin-Hai et al. 2003; Shimizu and Hitt 2004; Carvalho et al. 2017; Gunasekaran et al. 2019; Battistella et al. 2017; Plonka 1997*
	Participants of the agile operations training are familiar with an appropriate performance management for the concept of agile operations	- Participants experience the to-be state with the chosen agile operations levers and the developed roles and responsibilities at the learning factory - Participants discuss based on a qualitative scorecard performance management approach the impact of the elaborated improvements throughout the course.	- Performance management approach across different company levels - Scorecard dimensions to track agile operations activities	- Track agile operations activities is needed in order to continuously further improve the overall system - Governance structure is needed to coordinate agility as cross-functional approach	*Ramsauer et al. 2017; Zhang and Sharifi 2000; Sahebjamnia et al. 2018 Vokurka and Fliedner 1998; Nejatian et al. 2018; Tiwari R.K and Tiwari J.K. 2019; Shimizu and Hitt 2004; Carvalho et al. 2017*

Appendix E: Learning Factory Requirements[24]



1. Operating model	1.1 Operator	Academic institution			Non-Academic institution					Profit oriented operator						
		University	College	BA	Vocational school/high school	Chamber	Union	Employer association	Industrial network	Consulting	Producing company					
	1.2 Trainer	Professor	Researcher	Student assistant	Technical expert/int. specialist	Consultant	Educationalist									
	1.3 Content	Own development	External assisted development	External development												
	1.4 Initial funding	Internal funds	Public funds	Company funds												
	1.5 Ongoing funding	Internal funds	Public funds	Company funds												
	1.6 Funding continuity	Short term funding (e.g., single events)	Mid-term funding (projects and programs <3 years)	Long-term funding (projects and programs >3 years)												
	1.7 Business model for trainings	Open models			Closed models (training program only for single company)											
		Club model	Course fees	BA												
2. Purpose and targets	2.1 Main purpose	Education	Vocational training	Research												
	2.2 Secondary purpose	Test environment/pilot environment	Industrial production	Innovation transfer	Advertisement for production											
	2.3 Target groups for education and training	Pupils	Students			Employees							Profit oriented operator			
			Bachelor	Master	PhD students	Apprentices	Skilled workers	Semi-skill. workers	Un-skilled workers	Lower mgmt	Middle mgmt	Top mgmt	Entrepreneurs	Freelancer	Unemployed	Open public
	2.4 Group constellation	Homogenous	Heterogeneous (knowledge level, hierarchy, students + employees, etc.)													
	2.5 Targeted industries	Mechanical & plant eng.	Automotive	Logistics	Transportation	FMCG	Aerospace									
		Chemical industry	Electronics	Construction	Insurance/banking	Textile industry	…									
	2.6 Subject-rel. learning contents	Prod. Mgmt & organization	Resource efficiency	Lean mgmt	Automation	CPPS	Work system design	HMI	Design	Intralogistics design & mgmt	…					
	2.7 Role of LF for research	Research object	Research enabler													
	2.8 Research topics	Prod. management & organization	Resource efficiency	Lean mgmt	Automation	CPPS	Changeability	HMI	Didactics	…						
3. Process	3.1 Product lifecycle	▒ Product planning	▒ Product development	▒ Product design	▒ Rapid prototyping	■ Manufacturing	■ Assembly	■ Logistics	▒ Service	▒ Recycling						
	3.2 Factory lifecycle	▒ Investment planning	▒ Factory concept	▒ Process planning	▒ Ramp-up				▒ Maintenance	▒ Recycling						
	3.3 Order lifecycle	▒ Configuration & order	▒ Order sequencing	▒ Production planning and scheduling					▒ Picking, packaging	▒ Shipping						
	3.4 Technology lifecycle	▒ Planning	▒ Development	▒ Virtual testing					▒ Maintenance	▒ Modernization						
	3.5 Indirect functions	▒ SCM	▒ Sales	▒ Purchasing	▒ HR	▒ Finance/controlling	▒ QM									
	3.6 Material flow	▨ Continuous production	Discrete production													
	3.7 Process type	Mass production	Serial production	Small series production	One-off production											
	3.8 Manufacturing organization	Fixed-site manufacturing	Work-bench manufacturing	Workshop manufacturing	Flow production											
	3.9 Degree of automation	■ Manual	▒ Partly automated/hybrid automation	▒ Fully automated												
	3.10 Manufacturing methods	Cutting	Trad. primary shaping	Additive manufacturing	Forming	Joining	Coating	Change material properties								
	3.11 Manufacturing technology	■ Physical	▨ Chemical	▨ Biological												
4. Setting	4.1 Learning environment	■ Purely physical (planning + execution)	Physical LF supported by digital factory (see line "IT-integration")	Physical value stream of LF extended virtually	▨ Purely virtual (planning + execution)											
	4.2 Environment scale	Scaled down	Life-size													
	4.3 Work system levels	■ Work place	■ Work system	▒ Factory	▒ Network											
	4.4 Enablers for changeability	▒ Mobility	▒ Modularity	▒ Compatibility	▒ Scalability	▒ Universality										
	4.5 Changeability dimensions	▒ Layout and logistics	▒ Product features	▒ Product design	▒ Technology	▒ Product quantities										
	4.6 IT-integration	▒ IT before SOP (CAD, CAM, simulation)	▒ IT after SOP (PPS, ERP, MES)	▒ IT after production (CRM, PLM …)												
5. Product	5.1 Materiality	■ Material (physical product)	Immaterial (service)													
	5.2 Form of product	General cargo	Bulk cargo													
	5.3 Product origin	Own development	Development by participants	External development												
	5.4 Marketability of product	Available on the market	Available on the market but didactically simplified	Functional, could be available on the market	Without function/application, for demonstration only											
	5.5 No. of different products	1 product	■ 2 products	▒ 3-4 products	▒ >4 products	▨ Flexible, developed by participants	▨ Acceptance of real orders									
	5.6 No. of variants	1 variant	■ 2-4 variants	▒ 4-20 variants	…	▨ Flexible, depending on participants	▨ Determined by real orders									
	5.7 No. of components	1 comp.	2-5 comp.	■ 6-20 comp.	▒ 21-50 comp.	▒ 51-100 comp.	▒ >100 comp.									
	5.8 Further product use	Re-use/re-cycling	Exhibition/display	Give-away	Sale	Disposal										
6. Didactics	6.1 Competence classes	Technical and methodological competencies	Social and communication competencies	Personal competencies	Activity and implementation oriented competencies											
	6.2 Dimensions learning targets	Cognitive	Affective	Psycho-motorical												
	6.3 Learn. scenario strategy	Instruction	Demonstration	Closed scenario	Open scenario											
	6.4 Type of learn. environment	Greenfield (development of factory environment)	■ Brownfield (improvement of existing factory environment)													
	6.5 Communication channel	■ Onsite learning (in the factory environment)	▨ Remote connection (to the factory environment)													
	6.6 Degree of autonomy	Instructed	Self-guided/self-regulated	Self-determined/self-organized												
	6.7 Role of the trainer	Presenter	Moderator	Coach	Instructor											
	6.8 Type of training	Tutorial	Practical lab course	Seminar	Workshop	Project work										
	6.9 Standardization of trainings	Standardized trainings	Customized trainings													
	6.10 Theoretical foundation	Prerequisite	In advance (en bloc)	Alternating with practical parts	Based on demand	Afterwards										
	6.11 Evaluation levels	Feedback of participants	Learning of participants	Transfer to the real factory	Economic impact of trainings	Return on trainings/ROI										
	6.12 Learning success evaluation	Knowledge test (written)	Knowledge test (oral)	Written report	Oral presentation	Practical exam	None									
7. Metrics	7.1 No. of participants per training	1-5 participants	5-10 participants	10-15 participants	15-30 participants	>30 participants										
	7.2 No. of standardized trainings	1 training	2-4 trainings	5-10 trainings	>10 trainings											
	7.3 Aver. duration of a single training	<1 day	1-2 days	3-5 days	5-10 days	10-20 days	>20 days									
	7.4 Participants per year	<50 participants	50-200 participants	201-500 participants	501-1000 participants	>1000 participants										
	7.5 Capacity utilization	<10%	10-20%	21-50%	51-75%	76-100%										
	7.6 Size of LF	<100 sqm	100-300 sqm	300-500 sqm	500-1000 sqm	>1000 sqm										
	FTE in LF	<1	2-4	5-9	10-15	>15										

☐ No influence on minimum requirements
▨ No conclusion possible
▒ Beneficial
■ Required

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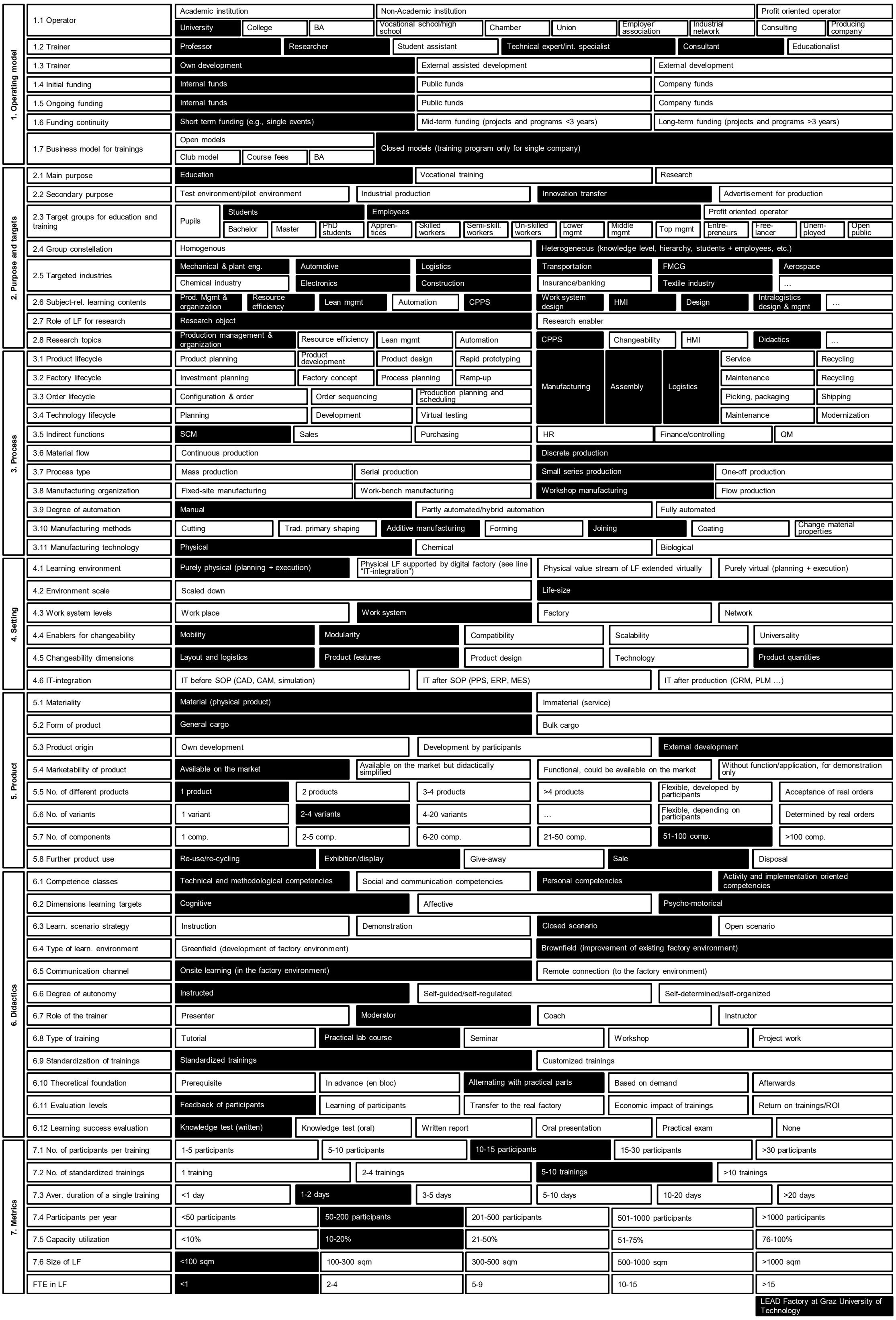
[24] Qualitative, based on learnings from this research study (adapted from Abele et al. 2019, pp. 100–118)

Appendix F: LEAD Factory pre-study setup[25]



1. Operating model	1.1 Operator	Academic institution			Non-Academic institution					Profit oriented operator						
		University	College	BA	Vocational school/high school	Chamber	Union	Employer' association	Industrial network	Consulting	Producing company					
	1.2 Trainer	**Professor**	**Researcher**	Student assistant	**Technical expert/int. specialist**	**Consultant**	Educationalist									
	1.3 Trainer	**Own development**	External assisted development	External development												
	1.4 Initial funding	**Internal funds**	Public funds	Company funds												
	1.5 Ongoing funding	**Internal funds**	Public funds	Company funds												
	1.6 Funding continuity	**Short term funding (e.g., single events)**	Mid-term funding (projects and programs <3 years)	Long-term funding (projects and programs >3 years)												
	1.7 Business model for trainings	Open models			**Closed models (training program only for single company)**											
		Club model	Course fees	BA												
2. Purpose and targets	2.1 Main purpose	**Education**	Vocational training	Research												
	2.2 Secondary purpose	Test environment/pilot environment	Industrial production	**Innovation transfer**	Advertisement for production											
	2.3 Target groups for education and training	Pupils	**Students**			**Employees**						Profit oriented operator				
			Bachelor	Master	PhD students	Appren-tices	Skilled workers	Semi-skill. workers	Un-skilled workers	Lower mgmt	Middle mgmt	Top mgmt	Entre-preneurs	Free-lancer	Unem-ployed	Open public
	2.4 Group constellation	Homogenous	**Heterogeneous (knowledge level, hierarchy, students + employees, etc.)**													
	2.5 Targeted industries	**Mechanical & plant eng.**	**Automotive**	**Logistics**	**Transportation**	**FMCG**	**Aerospace**									
		Chemical industry	**Electronics**	**Construction**	Insurance/banking	**Textile industry**	…									
	2.6 Subject-rel. learning contents	**Prod. Mgmt & organization**	**Resource efficiency**	**Lean mgmt**	Automation	**CPPS**	**Work system design**	**HMI**	**Design**	**Intralogistics design & mgmt**	…					
	2.7 Role of LF for research	**Research object**	Research enabler													
	2.8 Research topics	**Production management & organization**	Resource efficiency	Lean mgmt	Automation	**CPPS**	Changeability	HMI	**Didactics**	…						
3. Process	3.1 Product lifecycle	Product planning	Product development	Product design	Rapid prototyping	**Manufacturing**	**Assembly**	**Logistics**	Service	Recycling						
	3.2 Factory lifecycle	Investment planning	Factory concept	Process planning	Ramp-up				Maintenance	Recycling						
	3.3 Order lifecycle	Configuration & order	Order sequencing	Production planning and scheduling					Picking, packaging	Shipping						
	3.4 Technology lifecycle	Planning	Development	Virtual testing					Maintenance	Modernization						
	3.5 Indirect functions	**SCM**	Sales	Purchasing	HR	Finance/controlling	QM									
	3.6 Material flow	Continuous production	**Discrete production**													
	3.7 Process type	Mass production	Serial production	**Small series production**	One-off production											
	3.8 Manufacturing organization	Fixed-site manufacturing	Work-bench manufacturing	**Workshop manufacturing**	Flow production											
	3.9 Degree of automation	**Manual**	Partly automated/hybrid automation	Fully automated												
	3.10 Manufacturing methods	Cutting	Trad. primary shaping	**Additive manufacturing**	Forming	**Joining**	Coating	Change material properties								
	3.11 Manufacturing technology	**Physical**	Chemical	Biological												
4. Setting	4.1 Learning environment	**Purely physical (planning + execution)**	Physical LF supported by digital factory (see line "IT-integration")	Physical value stream of LF extended virtually	Purely virtual (planning + execution)											
	4.2 Environment scale	Scaled down	**Life-size**													
	4.3 Work system levels	Work place	**Work system**	Factory	Network											
	4.4 Enablers for changeability	**Mobility**	**Modularity**	Compatibility	Scalability	Universality										
	4.5 Changeability dimensions	**Layout and logistics**	**Product features**	Product design	Technology	**Product quantities**										
	4.6 IT-integration	IT before SOP (CAD, CAM, simulation)	IT after SOP (PPS, ERP, MES)	IT after production (CRM, PLM …)												
5. Product	5.1 Materiality	**Material (physical product)**	Immaterial (service)													
	5.2 Form of product	**General cargo**	Bulk cargo													
	5.3 Product origin	Own development	Development by participants	**External development**												
	5.4 Marketability of product	**Available on the market**	Available on the market but didactically simplified	Functional, could be available on the market	Without function/application, for demonstration only											
	5.5 No. of different products	**1 product**	2 products	3-4 products	>4 products	Flexible, developed by participants	Acceptance of real orders									
	5.6 No. of variants	1 variant	**2-4 variants**	4-20 variants	…	Flexible, depending on participants	Determined by real orders									
	5.7 No. of components	1 comp.	2-5 comp.	6-20 comp.	21-50 comp.	**51-100 comp.**	>100 comp.									
	5.8 Further product use	**Re-use/re-cycling**	**Exhibition/display**	Give-away	**Sale**	Disposal										
6. Didactics	6.1 Competence classes	**Technical and methodological competencies**	Social and communication competencies	**Personal competencies**	**Activity and implementation oriented competencies**											
	6.2 Dimensions learning targets	**Cognitive**	Affective	**Psycho-motorical**												
	6.3 Learn. scenario strategy	Instruction	Demonstration	**Closed scenario**	Open scenario											
	6.4 Type of learn. environment	Greenfield (development of factory environment)	**Brownfield (improvement of existing factory environment)**													
	6.5 Communication channel	**Onsite learning (in the factory environment)**	Remote connection (to the factory environment)													
	6.6 Degree of autonomy	**Instructed**	Self-guided/self-regulated	Self-determined/self-organized												
	6.7 Role of the trainer	Presenter	**Moderator**	Coach	Instructor											
	6.8 Type of training	Tutorial	**Practical lab course**	Seminar	Workshop	Project work										
	6.9 Standardization of trainings	**Standardized trainings**	Customized trainings													
	6.10 Theoretical foundation	Prerequisite	In advance (en bloc)	**Alternating with practical parts**	Based on demand	Afterwards										
	6.11 Evaluation levels	**Feedback of participants**	Learning of participants	Transfer to the real factory	Economic impact of trainings	Return on trainings/ROI										
	6.12 Learning success evaluation	**Knowledge test (written)**	Knowledge test (oral)	Written report	Oral presentation	Practical exam	None									
7. Metrics	7.1 No. of participants per training	1-5 participants	5-10 participants	**10-15 participants**	15-30 participants	>30 participants										
	7.2 No. of standardized trainings	1 training	2-4 trainings	**5-10 trainings**	>10 trainings											
	7.3 Aver. duration of a single training	<1 day	**1-2 days**	3-5 days	5-10 days	10-20 days	>20 days									
	7.4 Participants per year	<50 participants	**50-200 participants**	201-500 participants	501-1000 participants	>1000 participants										
	7.5 Capacity utilization	<10%	**10-20%**	21-50%	51-75%	76-100%										
	7.6 Size of LF	**<100 sqm**	100-300 sqm	300-500 sqm	500-1000 sqm	>1000 sqm										
	FTE in LF	**<1**	2-4	5-9	10-15	>15										

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[25] As published in Karre et al. 2017, p. 212

Appendix G: Business game lever impact

The following Figure 70 shows in more detail which lever and lever combination has a positive impact on the added scenarios. Several of the enumerated levers have a further impact on the physical learning factory exercise (exercise #10).

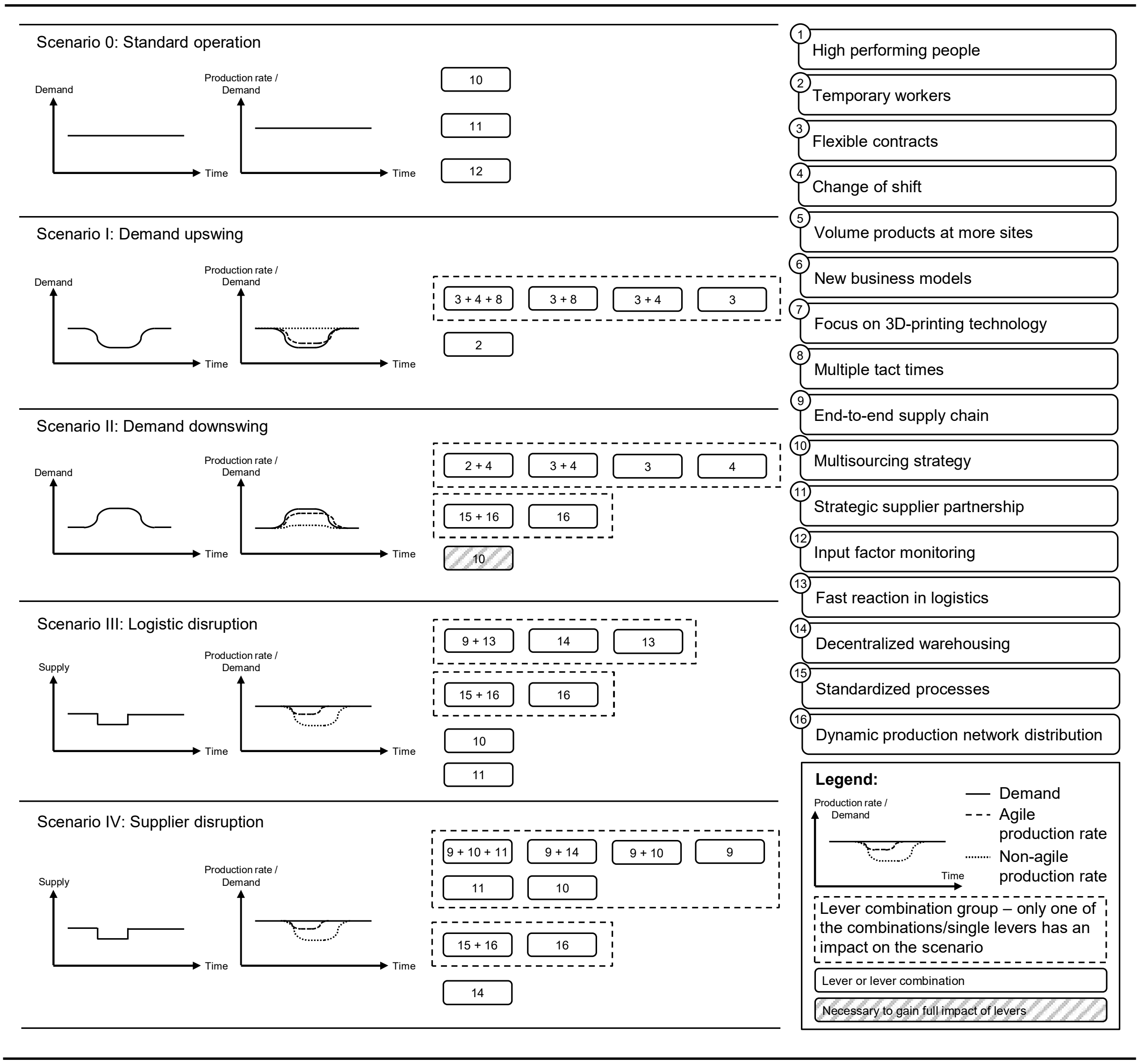

Figure 70: Business game lever impact (adapted from Rinnhofer 2021, p. 34)

Appendix H: Training actions schedules

Training action #1

Time	Training	Type
08:30 – 09:00	Need for action	Theory
09:00 – 10:00	Experience uncertainties	Exercise
10:00 – 10:15	*Coffee break*	
10:15 – 10:45	Uncertainties – areas of origin	Theory
10:45 – 11:30	Identify uncertainties	Exercise
11:30 – 11:45	Uncertainties – effects on operations	Theory
11:45 – 12:15	Assess & prioritize uncertainties	Exercise
12:15 – 13:15	*Lunch break*	
13:15 – 13:45	Monitoring as pre-requisite for agile operations	Theory
13:45 – 14:45	Setup a monitoring system	Exercise
14:45 – 15:00	Wrap-up & key takeaways	Discussion

Figure 71: Training action #1 schedule (‘part A: Sensing’)

Training action #2

Time	Training	Type
08:15 – 08:45	Need for action	Theory
08:45 – 09:45	Experience uncertainties	Exercise
09:45 – 10:00	*Coffee break*	
10:00 – 10:30	Understand & assess uncertainties*	Theory
10:30 – 11:00	Strategic alignment	Theory
11:00 – 12:30	Rate current system & create agility A	Exercise
12:15 – 13:30	*Lunch break*	
13:30 – 14:00	Define the agility need level	Exercise
14:00 – 14:30	Governance & Organization	Theory
14:30 – 14:45	*Coffee break*	
14:45 – 16:30	Define roles & implement agility	Exercise
16:30 – 16:45	Wrap-up & key takeaways	Discussion

*Summary of theory and introduction to exercise results of ‘part A: Sensing’

Figure 72: Training action #2 schedule ('part B: Responding')

Training action #3 & #4

Time	Training	Type
08:30 – 09:00	Need for action	Theory
09:00 – 10:15	Create awareness	Exercise #1
10:15 – 10:30	*Coffee break*	
10:30 – 11:00	Uncertainties – areas of origin	Theory
11:00 – 12:00	Understand uncertainties A-identification	Exercise #2
12:00 – 13:00	*Lunch break*	
13:00 – 13:30	Uncertainties – effects on operations	Theory
13:30 – 14:15	understand uncertainties B-prioritization	Exercise #3
14:15 – 14:45	Monitoring as pre-requisite for agile operations	Theory
14:45 – 15:00	*Coffee break*	
15:00 – 16:15	Monitoring	Exercise #4
16:15 – 16:30	Wrap-up & key takeaways	Discussion

Figure 73: Training action #3 & #4 – day 1

Time	Training	Type
08:15 – 08:30	Operations functions	Theory
08:30 – 09:15	Adapt operations – new product	Exercise #5
09:15 – 09:45	Strategic alignment I	Theory
09:45 – 10:15	Rate current system - agility index	Exercise #6
10:15 – 10:30	*Coffee break*	
10:30 – 10:45	Agile operations levers & lever combinations	Theory
10:45 – 12:00	Create agility – lever identification	Exercise #7
12:00 – 13:00	*Lunch break*	
13:00 – 13:15	Strategic alignment II	Theory
13:15 – 14:30	Define agility need level	Exercise #8
14:30 – 14:45	Governance & Organization	Theory
14:45 – 15:00	*Coffee break*	
15:00 – 15:45	Define roles & responsibilities	Exercise #9
15:45 – 17:00	Implement agile operations	Exercise #10
17:00 – 17:15	Wrap-up & key takeaways	Discussion

Figure 74: Training action #3 & #4 – day 2

Appendix I: Publications

1. Karre H, Hammer M, Ramsauer C. Building capabilities for agility in a learning factory setting. Procedia Manufacturing 2019; 31:60–65.
2. Hulla M, Hammer M, Karre H, Ramsauer C. A case study based digitalization training for learning factories. Procedia Manufacturing 2019; 31:169–174.
3. Hulla M, Karre H, Hammer M, Ramsauer C. A Teaching Concept Towards Digitalization at the LEAD Factory of Graz University of Technology. In: Auer ME, Tsiatsos T, editors. The Challenges of the Digital Transformation in Education: Proceedings of the 21st International Conference on Interactive Collaborative Learning (ICL2018) - Volume 2. Cham: Springer International Publishing; 2019. p. 393–402 (Advances in Intelligent Systems and Computing; vol. 917).
4. Gotthardt S, Hulla M, Eder M, Karre H, Ramsauer C. Digitalized milk-run system for a learning factory assembly line. Procedia Manufacturing 2019; 31(2):175–179.
5. Auberger E, Karre H, Ramsauer C. Introduction of a new product in an operating assembly process at Graz University of Technology´s LEAD Factory. Procedia Manufacturing 2019; 31(622):103–108.
6. Hammer M, Karre HD, Ramsauer C. Resource-productive operations - how lean, green and constraint management approaches blend together. Annals of Faculty Engineering Hunedoara – International Journal of Engineering 2018; 16(1):87–92.
7. Karre H, Hammer M, Ramsauer C. Learn how to cope with volatility in operations at Graz University of Technology's LEAD Factory. Procedia Manufacturing 2018; 23:15–20.
8. Karre H, Hammer M, Kleindienst M, Ramsauer C. Transition towards an Industry 4.0 State of the LeanLab at Graz University of Technology. Procedia Manufacturing 2017; 9:206–213.
9. Karre HD, Böhm T, Friessnig MH, Ramsauer C. Academic teaching at digital fabrication laboratories in the field of mechanical engineering. In: EDULEARN16 Proceedings: 8th International Conference on Education and New Learning Technologies: IATED; 2016. p. 8844–8853.