Master Thesis

Innovative approaches to reduce the processing time for assembling the modular kit engines at BMW.

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Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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Steyr, im April 2015

Abstract

The assembly line for four- and six-cylinder petrol engines in the modular kit design is part of BMW's new engine production network. With a takt time just below one minute, the production output of assembly line B/G/E should be 495 engines per shift. At the beginning of this thesis in October 2014, the engine assembly line located in Steyr was in pilot production with approximately 50 engines produced per week. The five areas of the engine assembly line vary in degree of automation, these include; the highly automated units such as short block and cylinder head assembly, the partly automated engine block assembly, the low automated final assembly, and lastly, the end-of-line-test, which is the final stage before engines are transported to an international car assembly factory.

The productivity monitoring of the engine production at BMW is via the processing time of the engines, which includes workers bound to takt, process support and rework. This thesis assesses the potential for increasing productivity in the very early stages before the start of production in April 2015.

The goal is to define and evaluate measures and concepts which support reaching the target processing time for assembling the B48 and B58 engines in line B/G/E. With the constant pressure of price competition, an annual productivity increase of 6% shall be realized and presented in a productivity roadmap for 2016 and 2017. All these measures are in line with BMW's strategies of "zero defects" and ergonomic aspects for workplace design.

A huge potential for productivity increase is distribution of work content, so called assembly line balancing. Investigated in this thesis will be lean manufacturing principles coupled with industrial engineering tools, such as methods time measurement (MTM). Intense process analyses in the different areas using chalk circles and other methods are conducted to identify waste and potentials for improvement. Beyond that, various innovative methods and solutions already existing at BMW are incorporated in this thesis.

Kurzfassung

Die Montagelinie in Steyr für vier- und sechszylinder Benzinmotoren im Baukastendesign ist Teil des neuen BMW-Produktionsnetzwerkes. Mit einer Taktzeit unter einer Minute soll die Ausbringung der Montagelinie B/G/E 495 Motoren pro Schicht betragen. Am Beginn der Masterarbeit im Oktober 2014 war die Linie in Steyr in Vorserienproduktion mit einer Wochenstückzahl von ungefähr 50 Motoren. Die fünf Bereiche der Montagelinie unterscheiden sich stark im Automatisierungsgrad. Die Motoren fließen von den hochautomatisierten Bereichen Short Block- und Zylinderkopfmontage über die moderat automatisierte Rumpfmontage hin zur niedrig automatisierten Fertigmontage und zuletzt in das Prüffeld, bevor sie in ein internationales Fahrzeugwerk verschickt werden.

Die Produktivitätsüberwachung in der Motorenproduktion bei BMW geschieht über die Fertigungszeit pro Motor, welche taktgebundene Mitarbeiter genauso wie Prozessunterstützung und Nacharbeit enthält. Diese Masterarbeit soll bereits in einer sehr frühen Phase der Produktion, vor Serienanlauf im April 2015, Potentiale zur Steigerung der Produktivität feststellen.

Das Ziel ist es, Maßnahmen und Konzepte zu definieren und zu evaluieren, um die Erreichung der Zielfertigungszeit für die Montage der B48 und B58 Motoren zu unterstützen. Durch den allgegenwärtigen Preisdruck der Konkurrenz soll eine jährliche Produktivitätssteigerung von 6% realisiert und in Form einer Produktivitätsroadmap für 2016 und 2017 dargestellt werden. Die definierten Ziele sollen unter besonderer Beachtung der Qualitätsanforderungen bei BMW in Richtung „Null Fehler“ und ergonomische Arbeitsplatzgestaltung ausgearbeitet werden.

Ein großes Potential zur Steigerung der Produktivität liegt in der Verteilung der Arbeitsvorgänge, der sogenannten Austaktung. Zusammen mit Prinzipien der schlanken Produktion (Lean manufacturing) und Werkzeugen der Arbeitswissenschaften (Industrial engineering), wie Methods Time Management (MTM), bilden diese die Grundlage für die Masterarbeit. Intensive Prozessanalysen in den verschiedenen Bereichen, unter Einsatz von Kreidekreisen oder anderen Methoden, werden durchgeführt, um Verbesserungspotentiale zu identifizieren. Darüber hinaus werden verschiedene innovative Methoden und Lösungen, die bei BMW zum Einsatz kommen, in dieser Masterarbeit eingearbeitet.

Contents

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Abbreviations

3P	Production preparation process
C/T	Cycle time
CAPP	Computer-aided process planning
DPM	Direct Part Mark
EMS	Electric Monorail System
IE	Industrial Engineering
JIS	Just-in-sequence
JIT	Just-in-time
LCIA	Low-cost intelligent automation
MTM	Methods Time Measurement
nOK	Not OK
OEE	Overall Equipment Effectiveness
PDM	Product Data Management
PEP	Product Engineering Process
SOP	Start of production
T/B	Takt balance
TMU	Time Measurement Unit
TPS	Toyota Production System
VANOS	Variable camshaft control
VPS	Value-added Production System
VVT	Variable Valve Timing
W/S	Workstation
WIP	Work in progress
WPC	Workpiece carrier

1. Introduction

1.1. About BMW Plant Steyr

Since 1979, the BMW engine plant in Steyr has been a fundamental part of the BMW Group's production network. It is the largest engine plant of the BMW group and the competence center for BMW's diesel engine development. Three-, four- and six-cylinder diesel engines, as well as, three- and six-cylinder petrol engines, are produced and assembled there. The engines are first built for BMW and Mini cars at the BMW plant Steyr, then delivered to international automotive assembly plants. (BMW Motoren GmbH, 2014b)

At peak times, around 5000 engines per day are assembled and over 1000 variants are covered. The assembly department has a total of 1400 employee and a total of 16,2 million engines have been produced since Start of production (SOP) in 1982. (BMW Motoren GmbH, 2014a)

High-performance flexibility is due to volatile market conditions a fundamental success factor for the production in Steyr. To reach an optimum in flexibility, the BMW plant in Steyr will further develop its production lines and innovative working time models. (Ebner, 2014)

1.2. Initial situation

The initial situation of this thesis starts with describing the new modular kit engine generation, developed at BMW. Subsequently the assembly line for the four- and six-cylinder modular kit engines in Steyr will be introduced.

1.2.1. The modular kit engine at BMW

With the development of the direct fuel injection and turbo charging technology for the gasoline engines in previous years, the design for gasoline and diesel engines converged. The strong increase of vehicle derivatives and volatile reacting markets in regard to model mix caused BMW to respond with the development of a highly promising new modular product and process design.

The new engine generation covers three-, four- and six- cylinder gasoline and diesel versions for the entire BMW vehicle portfolio (Steinparzer et al., 2014, p. 62)

BMW strives for an increase in flexibility of its manufacturing network with the introduction of the new modular kit (in German = “Baukasten”) engine generation. Uniform interfaces and a low number of variants enable the use of the engines in a broad range of vehicle derivatives to create synergies in the process chain from development to purchasing and production. The complexity was reduced, due to standardized production processes of the modular kit engine, therefore BMW’s production factories can react with high flexibility to future market demands. (Ardey et al., 2014, p. 125)

The introduction of the modular kit engine was strongly influenced by emission legislation (EU6 RDE / US LEV3), CO_2 regulation for individual vehicles and the entire fleet as well as fuel consumption and production costs of the drive systems. BMW designed the new gasoline and diesel modular kit engine in order to meet these different requirements.

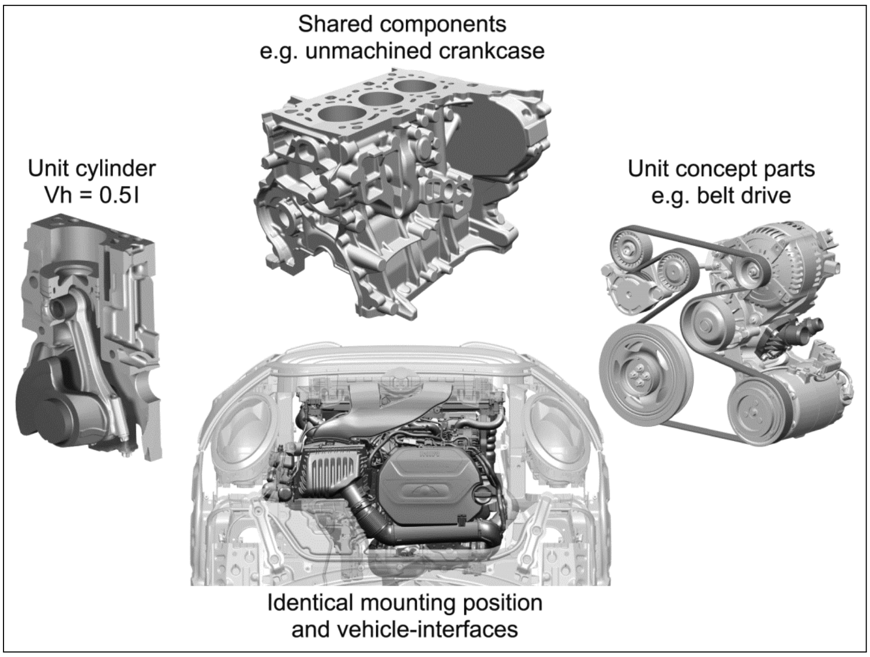


Figure 1.: Major characteristics of the modular kit engine (Ardey et al., 2014, p. 128)

The characteristics of the common gasoline-diesel family include a large number of components based on the same concept, identical components, as well as uniform interfaces and installation locations in the vehicle. These aim to achieve simple and rapid implementation of different variants on the same base engine and high flexibility across different production facilities. This includes strong synergy effects for development, investment in production lines and purchasing. (Ardey et al., 2014, p. 127; Steinparzer et al., 2014, p. 64) Figure 1 shows the major characteristics of the modular kit such as a standard cylinder with a capacity of 0,5 liters, shared unmachined components, unit concept parts like the belt drive, identical mounting positions and vehicle interfaces. (Ardey et al., 2014, p. 127)

The amount of identical components and components with the same concept, lead to important synergy effects across the entire modular kit. These include the concept of three-, four- and six-cylinders, as well as gasoline and diesel derivatives. (Ardey et al., 2014, p. 131) Figure 2 demonstrates 30 to 40% of shared components between petrol and diesel engines, and over 60% of unit concept parts between three-, four- and six-cylinder derivatives.

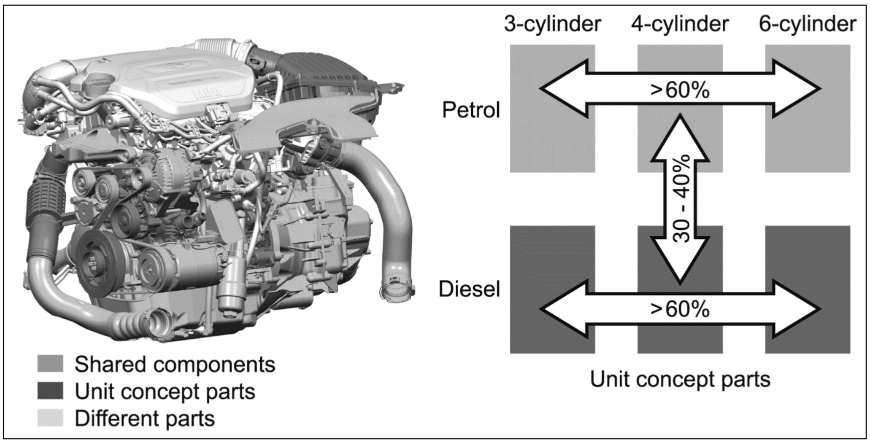


Figure 2.: Synergy effects of the modular kit engines (Ardey et al., 2014, p. 131)

The engines will further be addressed as B48 for the four-cylinder engine and B58 for the six-cylinder engine. "B" stands for modular kit engine ("Baukasten" in German). The second character represents the number of cylinders ("5" for six cylinders) and the third position for the type of fuel ("8" for petrol). Figure 3 shows the denotation of the B58 engine.

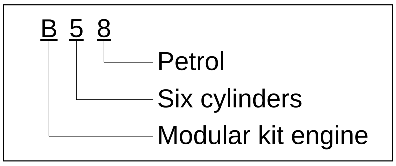


Figure 3.: Engine denotation

1.2.2. The assembly line for four- and six-cylinder petrol engines in Steyr

The assembly line B/G/E for the new generation of modular kit engines in Steyr will start serial production of B48 and B58 engines in April 2015. Line B/G/E is designed for producing 495 engines per shift with a duration of 8,3 hours and a resulting takt time just below one minute. The product mix is defined as constant production of 60% B48 and 40% B58 engines for this thesis. The anticipated production program is one shift until the end of 2015, two shifts in 2016 and will increase to a three shift production in 2017. Figure 4 shows a B58 engine, which is assembled in line B/G/E. At the start of this thesis the assembly line is in pilot production with a weekly output of approximately 50 engines.

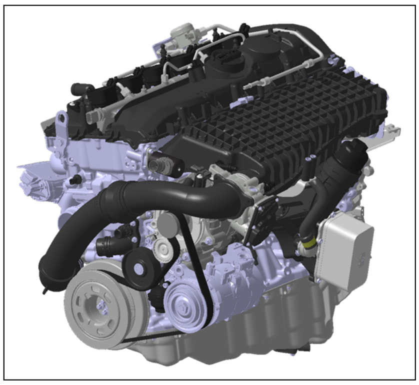


Figure 4.: B58 - six cylinder petrol engine (BMW Group, 2012)

Figure 5 shows the five areas of the assembly line B/G/E in Steyr. The main parts assembled in line B, the so-called *short block assembly*, are the crankcase, crankshaft, piston and connecting rod. The *cylinder head* with camshafts and valves is assembled in Line G. Both are pre-assembly lines for line E, with a high degree of automation. In the partly automated line E, the *engine block* is produced by combining short block with cylinder head and components such as oil sump, oil pump and water pump among others. Components like exhaust turbocharger, intake system, automotive wiring harnesses, with other attachment parts are assembled to the engine block in the *final assembly*. Friction coefficient of the camshaft, valve lift distribution, leak-tightness and engine functions including the electrical system are tested in the *end-of-line test*, which is the final stage before engines are transported to an international car assembly factory.

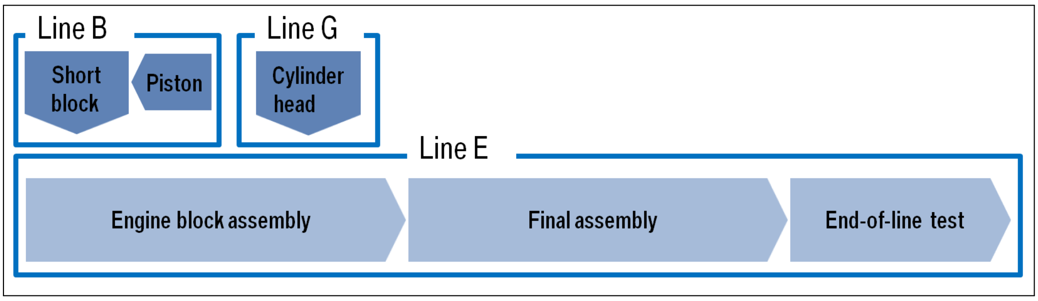


Figure 5.: Modular kit engine assembly line at BMW (BMW Group, 2012)

The foundation for the assembly line B/G/E is a *reference production system* developed at BMW for the modular kit architecture of three-, four- and six-cylinder petrol and diesel engines. The concept is that high-cost countries in BMW's existing engine production network in Munich, Steyr and Hams-Hall produce a yearly output of 450 to 600 thousand units. The basic premise of the reference system is the highest possible compliance with the assembly sequence, latest possible customization in the production process and earliest possible error detection. (BMW Group, 2012)

1.3. Scope and target definition

Out of the five areas of production, this thesis investigates line G, the cylinder head assembly; line E, the engine block assembly, parts of the final assembly and the end-of-line-test. The focus is on the manual workstations and reduction of waste, hence the non-value-added time.

The goal is to define and evaluate measures and concepts which support reaching the target processing time for assembling the B48 and B58 engines in line B/G/E. With the constant pressure of price competition, an annual productivity increase of 6% shall be realized and presented in a productivity roadmap for 2016 and 2017. All these measures are in line with BMW's strategies of "zero defects" and ergonomic aspects for workplace design.

1.4. Structure and approach

The productivity monitoring of the engine production at BMW is via the processing time of the engines, which includes workers bound to takt, process support, such as foremen and machine operators, and rework. Thus the main topics of this thesis analyze the potential for productivity increase assembling the modular kit engines are line balancing and methods of lean manufacturing defined in the Value-added Production System (VPS) of BMW.

Using synergies and lessons learned form existing engine assembly lines and BMW's best practice platform, as well as knowledge from experienced workers, are an essential source for finding improvement potentials. Thus visits of line 5/6 for sic-cylinder petrol engines, and line C for three-cylinder petrol and diesel modular kit engines in Steyr and line D/F for three- and four-cylinder petrol modular kit engines in Munich are conducted to incorporate measures and best practice solutions for the new assembly line in Steyr.

After studying the assembly line and assembled components in the different areas, work flows, work-load distribution and line balance are analyzed with lean manufacturing methods and tools like Production preparation process (3P) and process analysis, to optimize work stations and reduce waste. Concepts for innovative solutions are used to go beyond common paths for increasing productivity.

Chapter 2 provides the theoretical framework for this thesis reviewing state-of-the-art literature. The project at BMW is described in detail in Chapter 3, presenting tools and methods, as well as application of use. Chapter 4 summarizes the results of the work at BMW and leads to a conclusion in Chapter 5 and an outlook in Chapter 6.

2. Literature review

This chapter elaborates on the theoretical background for this thesis. The origin of lean manufacturing is described, by examining the evolution of the different manufacturing systems and the applied principles. Further on, the elements of modern lean production systems are described as a foundation for assembly lines. The end of this chapter will complete the literature review outlining the necessary background in industrial engineering for the thesis.

2.1. From manufacturing to lean manufacturing

The industrial revolution began in 1760 in Britain with the invention of the steam engine and continued until 1830. The economy changed form handicraft to an industry based on manufacturing. (Groover, 2008, p.26) Prior to this time in Europe, the majority of manufacturing was single-unit production based on manual manufacturing or simple machines. The industrial revolution increased productivity by increasing the mechanization of manual work. (Ramsauer, 2009, p. 7ff)

2.1.1. Single-unit production

The oldest form of production is represented by single-unit production, which requires special skills to manufacture a product. Universal tools made manufacturing very flexible and the costs of the product depended on the time required by the craftsman and the cost of the raw material. (Ramsauer, 2009, p. 9ff)

The industrialization of single-unit production started with Watt's steam engine and the development of machine tools for boring, turning, drilling, milling and shaping. Universal machines arranged and grouped according to the shop-floor principle characterize the single-unit production. (Groover, 2008, p.26; Ramsauer, 2009, p. 9ff)

2.1.2. First mass production

Production with a quantity of 100.000 and more is called "mass production", whereas "serial production" is within a range of around 100 pieces produced. With large production quantities, cost of manufacturing can be significantly decreased and productivity increased. (Ramsauer, 2009, p. 11) The important concept of *interchangeable parts* was introduced in the United States, and hence it became known as the "American system" of manufacturing. (Groover, 2008, p.27) More principles characterizing this manufacturing system include *division of labor*, *focus on the production process* and the *use of specialized machines*. (Ramsauer, 2009, p. 12-14)

In single-unit production individual workers manufacture a product from the first to the last step. The production process in mass production is broken down into several steps and divided among workers; called *division of labor*. The work content becomes simpler, knowledge is spread among several workers and the importance for organizing work increases. (Ramsauer, 2009, p. 11-14) In these early stages, the methods to organize labor and control the workflow were less than scientific. They were mainly based on precedent and historical practice rather than efficiency. (Smith & Hawkins, 2004, p. 2)

Product design must guarantee *interchangeability of parts*, otherwise additional efforts will be inevitable. *»Division of labor and interchangeable parts are prerequisites for a manual assembly line.«* (Ramsauer, 2009, p. 13) To achieve productivity advantages, it is reasonable to focus on the production process and use appropriate machines. The demand of high production quality for interchangeable parts is much better provided by mechanization and automation. These specialized machines only operate economically at a high production volume, which is usually given with mass production. (Ramsauer, 2009, p. 12-14)

2.1.3. Advanced mass production

Frederick Taylor further developed the American system of manufacturing which reached its peak at the beginning of the 20th century due to applications by Isaac Singer, Andrew Carnegie and Henry Ford. (Ramsauer, 2009, p. 15-21) The beginning of Industrial Engineering in 1881 is accredited to Taylor's organization of manufacturing operations. Frank and Lilian Gilbreth refined these early methods and time-motion studies brought a quantitative approach to the contemporary manufacturing systems and processes. (Smith & Hawkins, 2004, p. 2; Groover, 2008, p.27; Hayes & Pisano, 1994, p.78)

It was Ford with his production engineer who developed the first commonly known production system on industrial scale. The assembly line of the Ford Model T was the most advanced manufacturing technology at the time. The production time for the Model T was reduced from 12 hours to approximately 2 hours. Productivity was increased by eliminating time consuming activities such as searching for tools and materials. Eliminating wasted time in the assembly process was the first occurrence of manufacturing and lean thinking. (Ramsauer, 2009, p. 15-21; Smith & Hawkins, 2004, p. 2)

The assembly line employed constant movement of parts, sub-assemblies and assemblies, called flow principle. The flow principle is where work is brought to fittingly equipped employees at each workstation. Thus the speed and tasks of individual workers determine the productivity, not the sourcing for material and tools. (Ramsauer, 2009, p. 15-21; Smith & Hawkins, 2004, p. 2) With the division of labor method, work contents are divided and equally distributed over the workstations of the assembly line. As all workstations are linked, problems at one workstation cause a stop of the entire assembly line, therefore job organization and planning are very important. The flow principle is still applied today and triggered to development of methods to calculate work contents and related required times in advance. (Ramsauer, 2009, p. 15-21)

An essential principle to achieve high profitability in mass production is product standardization. Assembly lines can specialize in standard products and each variation of the product lowers productivity due to additional organizational and changeover activities. In theory, shorter production times and higher production quality can be achieved at larger quantities, leading to economy of scale effects. The share of fixed costs for equipment and overhead expenses also declines per product manufactured. (Ramsauer, 2009, p. 15-21)

2.1.4. Mass customization

Today's customers want to choose from a portfolio of different products with minimal waiting times. In particular, European automotive companies offer a variety of vehicles in which many are tailored to the customer's desires. Modern automotive assembly lines manufacture vehicles in thousands of variants. (Ramsauer, 2009, p. 21-22) The focus in the mass production system was on stability and control. It shifted to *»creating variety and customization through flexibility and quick responsiveness«* in mass customization, so nearly all customers find what they want. This requires flexibility in the manufacturing process and the use of general purpose machinery, as specialized machines do not longer accommodate the needs of the production of individually customized goods. (Pine, 1999, p. 44-48)

In order to ensure productivity, the division of labor principle is still in place. The work contents tend to more complex, with customer-specific mass production. In order to operate the highly automated flexible production facilities and handle product changes, the workers must be highly skilled and educated. The stiff hierarchical organization of the Taylor system of manufacturing is often softened to a team-oriented organization. (Ramsauer, 2009, p. 29-33)

The production process is essential for the creation of customer value and should lead to excellence. Make-or-buy decisions define in-house production in addition to sourcing from suppliers, and are leading to a competitive advantage. Parts and modules of different variants, are manufactured by suppliers to allow the focus to be on core processes. Thus the principle of vertical integration, as for the Ford Model T, is no longer valid. Economy of scale effects in an early stage of the production process, by reducing complexity and late customization through modular design and interchangeable parts. Modular product architecture is another key aspect of mass customization. (Ramsauer, 2009, p. 29-33)

Flexible production facilities, often with a high degree of automation, allow consistent productivity and short times for changeover. These machines are typically tailored for a company to process a range of products according to a defined production program. The flow principle is used to optimize takt times, balance workstations well in the assembly line and it does not end at the factory's boundaries. (Ramsauer, 2009, p. 29-33) Figure 6 illustrates the different principles applied in the described manufacturing systems.

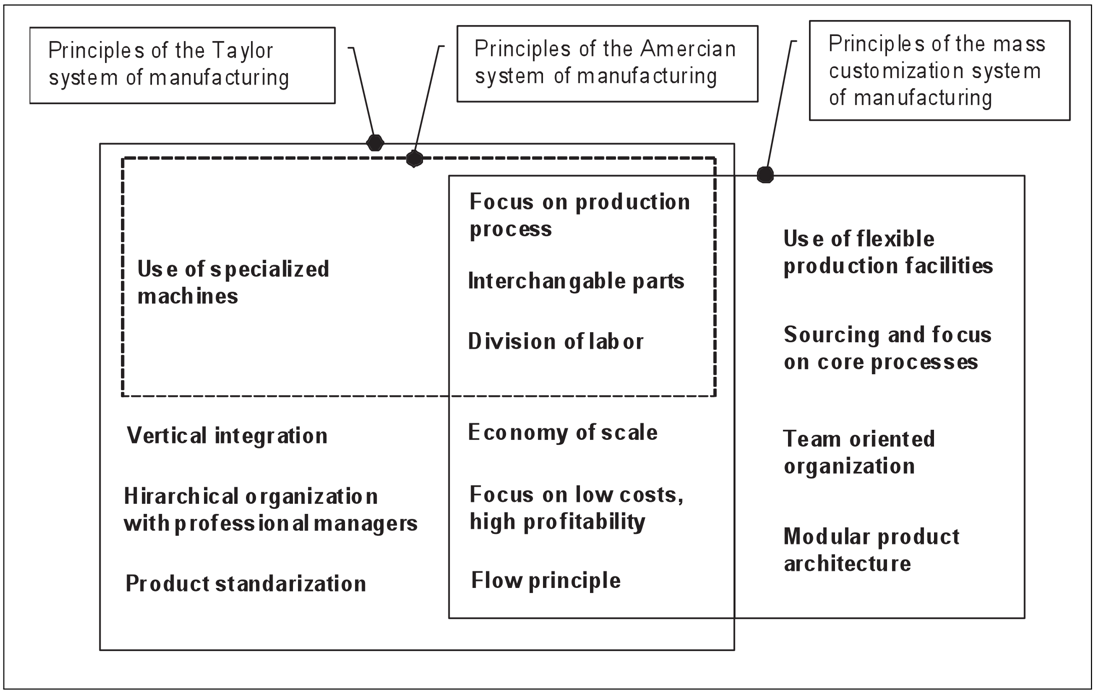


Figure 6.: Principles of manufacturing systems (Ramsauer, 2009, p. 29)

A high importance in the mass customization system of manufacturing are advances in management, towards the development of Just-in-time (JIT) delivery, early manufacturing involvement, cross-functional teams and lean production techniques. These factors increase *»flexibility and responsiveness and therefore the ability to increase variety and customization.«* (Pine, 1999, p. 48) To include global production sites and suppliers, the mass customization system of manufacturing uses JIT concepts like Kanban. (Ramsauer, 2009, p. 29-33)

2.1.5. Lean manufacturing

Based on Ford's production system the JIT concept – a network of suppliers capable of supplying components and material as needed for the production - was developed in Japan in the 1930s. Taiichi Ohno, widely known as the inventor of the Toyota Production System (TPS), implemented the assembly line concept and the supermarket system at the Japanese car manufacturing company Toyota. All of the present day Lean Manufacturing concepts are represented by the TPS. The Japanese improved the American manufacturing concepts such as waste elimination, standardized work practices, JIT systems and "Do it right the first time! (Quality control). (Smith & Hawkins, 2004, p. 6-8)

The term *Lean* was not coined by the people of Toyota, but by a research group at MIT analyzing the Toyota Production System (TPS). The group, led by James P. Womack published the book *The Machine That Changed the World* in 1990 and for the first time the term *Lean Manufacturing* was seen in print. (Smith & Hawkins, 2004, p. 10)

Lean Manufacturing means to produce in one process only as much as the next process needs, when it needs it. All processes, from raw material to the final customer, are linked in a smooth flow without detours to create the shortest lead time, highest quality and lowest costs. (Rother & Shook, 2003, p. 37) It is the practice of eliminating waste in every area with the goal of utilizing less human effort, less inventory, less time to develop products, and less space. (Smith & Hawkins, 2004, p. 16)

Figure 7 outlines the evolution of manufacturing form single-unit production of craftsmen to today's Modern Lean Manufacturing.

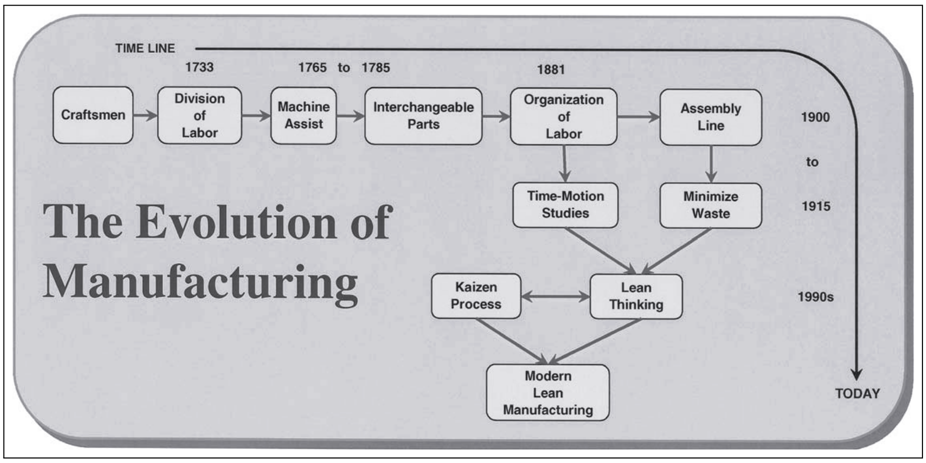


Figure 7.: The evolution of manufacturing (Smith & Hawkins, 2004, p. 4)

2.2. Elements of modern, lean production systems

An integral part of lean production systems are the applied manufacturing concepts and their interactions. The importance of just-in-time, just-in-sequence and one-piece-flow increased for companies to stay competitive with lean, customer-oriented and cost-optimized structures. (Dickmann, 2009, p. 16-18)

Eliminating waste was first practiced on the assembly line of the Ford Model T and this is where most "lean" companies start.

2.2.1. Eliminating waste

The key element of every lean production system is eliminating waste, or *muda* in Japanese. This philosophy is integral part of the Toyota Production System and distinguishes between activities that *add value* to a product or *non-value-added activities*, which the customer is not willing to pay for. The core question examining a manufacturing process always is *»What does the customer want from this process?«*. The customer is both, internal at the next step in the production line and the final (external) customer. Every processes - manufacturing, information or service - can be observed through the eyes of the customer to define value and separate the value-added tasks from the non-value-added. (Liker, 2004, p. 27)

Figure 8 shows waste or non-value-added operations of a truck chassis assembly line. The example shows that only a small number of tasks add value to the product. Some of the non-value-added tasks are incidental resp. necessary to perform value-added tasks; e.g. the operator has to reach and get the power tool to tighten the bolts. The key is to minimize the non-value-added operations by providing material and tools as close as possible to the point of assembly. (Liker, 2004, p. 28)

There are eight types of wastes according to Liker (2004, p. 28f) and Ortiz (2006, p. 27-32):

1. **Overproduction.** *»Producing more than is needed, faster than necessary, and before it is needed.«* (Ortiz, 2006, p. 28) Overproduction is the most common form of waste in a manufacturing environment. Producing without a customer order generates wastes as over-staffing, need for extra parts and material, accumulation of Work in progress (WIP) (with possible quality issues), excess inventory leading to storage and transportation cost. The ideal situation is to build products when needed, in a single piece flow and, knowing when to stop.

2. **Waiting.** Workers waiting during processing of a machine, or waiting for the next processing step to start, waiting for tools, parts, supplies, etc. or waiting because of stockouts, production delays, equipment downtime, or bottlenecks. Other reason for an operator to be idle is

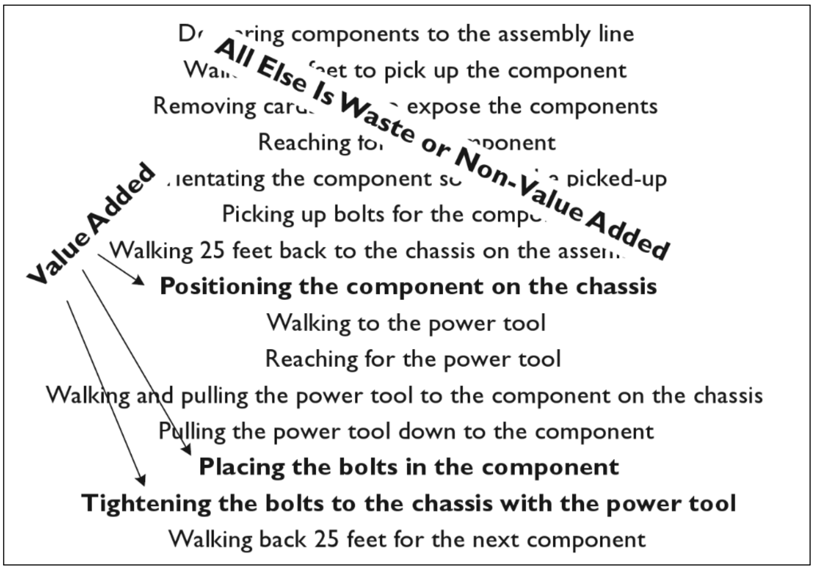


Figure 8.: Waste in a truck chassis assembly line (Liker, 2004, p. 28)

when the manufacturing processes are out of synchronization, imbalances in work content, inaccurate standards, and poor communication.

3. **Transportation.** Transportation requires manpower, forklifts, and paperwork caused by inefficient means of transport, moving raw material, parts, WIP, or finished goods into or out of the storage or between processes. Poor planning and scheduling can cause unnecessary transportation, as well as inefficient plant layouts for material supply to assembly lines.

4. **Overprocessing.** Overprocessing or incorrect processing are unneeded steps to process the parts. Unnecessary motion and defects due to poor tool or product design, or producing higher-quality products than necessary is also generating waste. Overprocessing can occur in part protection by packing, unpacking of parts repeatedly. Process wastes are more difficult to detect, since it requires detailed knowledge of the processes (Törenli, 2009, p.17).

5. **Inventory.** Any inventory beyond what is needed is waste. Longer lead times, damaged goods, transportation and storage costs, and delay are caused by excess raw material, parts, WIP, or finished goods. *»Also, extra inventory hides prolems such as production imbalances, late deliveries from suppliers, defects, equipment downtime, and long setup times.«* (Liker, 2004, p. 29) The reduction of wasted inventory will reduce required space leading to a significant reduction facility cost.

6. **Motion.** Unnecessary motion is any movement workers perform that does not add value to the product, such as walking or looking for and reaching for tools, parts, etc. As mentioned before, some motion is necessary to perform value-added tasks; it is still considered as wasteful.

7. **Defects/rework.** Every rework, scrap, replacement production and inspection is waste in terms of extra handling, time and effort. Product defects can be caused by poor line flow and layout, insufficient training, inaccurate standards, etc. The goal is to produce it right the first time, meaning possible defects must be identified as early as possible in the process.

8. **Unused human potential.** ot engaging or listening to employees can result in losing ideas, skills, opportunities for improvement and learning. Impacts on quality or productivity can be caused by not using individual employee potential or placing employees in positions where they are likely to produce errors or feel uncomfortable.

Figure 9 shows a simple time line for a casting, machining, and assembling process from raw material to finished parts. This simple transformation process illustrates a small portion of value-added tasks and a huge amount of waste along the value stream. (Liker, 2004, p. 29f)

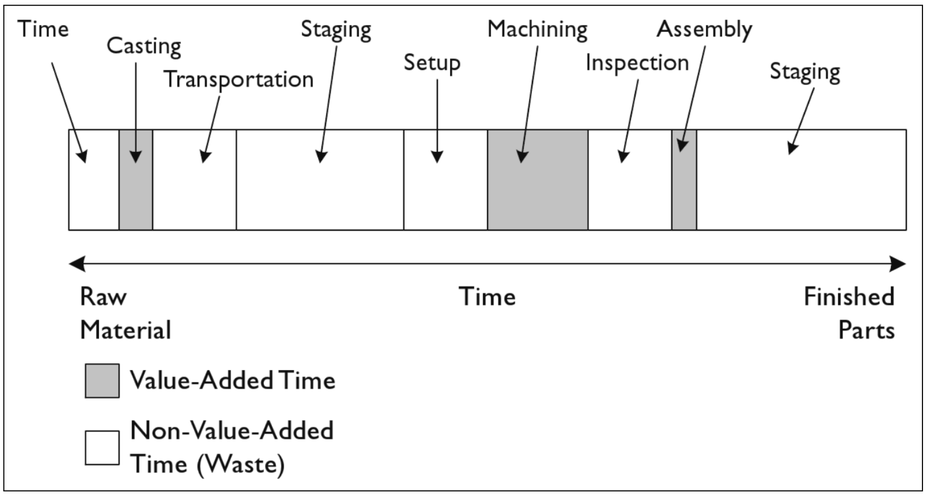


Figure 9.: Waste along the value stream (Liker, 2004, p. 30)

2.2.2. Just-in-time

As mentioned in Section 2.1.5, the JIT concept was developed in Japan and the general definition is to supply material at the right time, quality, quantity and place. Part of the philosophy is to use a holistic approach for optimizing production flows. (Dickmann, 2009, p. 16-18)

JIT in logistics is delivery of supply material and parts to the customer, even to the assembly line as usual in the automotive industry. The supplier is informed upfront about delivery time, quantity and sequence; often referred to as Just-in-sequence (JIS). JIT is not limited to logistics; it particularly includes manufacturing according to the flow principle with small material buffers or supermarkets and the actual customer demand. JIT-production is the core of the JIT-philosophy, but not as wide-spread as in logistics. The lead time is reduced by handling the product from one work cycle to the next without a stop and thus keeping the WIP at a minimum. This requires well-balanced production lines in order to handle a high product mix with different work contents and to operate the assembly lines at a certain production level. The foundations for JIT-production are one-piece-flow and the pull principle. (Dickmann, 2009, p. 16-18)

2.2.3. One-piece flow

Creating and implementing continuous flow in manufacturing is the beginning for any company in becoming lean. Flow is the key to lean by shortening the time from raw materials to finished goods and will lead to high quality, low cost and short delivery time. It also forces the implementation of other lean tools and principles such as built-in quality and preventive maintenance. (Liker, 2004, p. 87-96) Continuous flow means processing and moving one piece at a time, or a small and consistent batch, through a sequence of production steps. Each production step only produces what is requested by the next one. (LeanEnterpriseInstitute et al., 2008, p. 10)

Traditional manufacturing processes such as *batch-and-queue*, by contrast, often don't reveal what lean might accomplish as they have the capacity to hide vast inefficiencies. Large batches of material queue in the stages of the production process and wait for long periods of time until they are moved to the next stage. The value-added work takes a few hours at most; everything else is waste (muda). The goal of a lean environment is to create "one-piece-flow" and constantly cut out effort and time that is not adding value. (Liker, 2004, p. 87-96) This requires the efficient combination of manual and automated process steps, in order to increase the throughput, reduce the lead times and WIP,. (Gerberich, 2011, p. 137)

The raw materials flow, triggered by a customer order, immediately, just as needed to supplier plants, workers immediately fill the order with components. Further flowing to a production plant where workers assemble the order and immediately ship the finished product to the customer. One-piece-flow is applied where it fits an inventory buffers are carefully used where it does not fit. The ideal of flow means using small lots, having processes close together and keeping the material moving, which is by far better than producing large batches and creating huge inventory. (Liker, 2004, p. 87-96)

In traditional mass production, similar machines and similarly skilled people are grouped together to reach economies of scale and flexibility in scheduling operations. Managing the schedule for a welding department is easier than in one-piece-cells, as there is no need to predict what work may come up. This grouping requires material handling, and moving the most material possible each trip to efficiently utilize the process. From a lean perspective, this organization of production creates a lot of WIP inventory. Huge amounts of material sitting in inventory are often caused by overproduction in large batches, this often results in an ineffective use of space and concealment of problems. (Liker, 2004, p. 87-96)

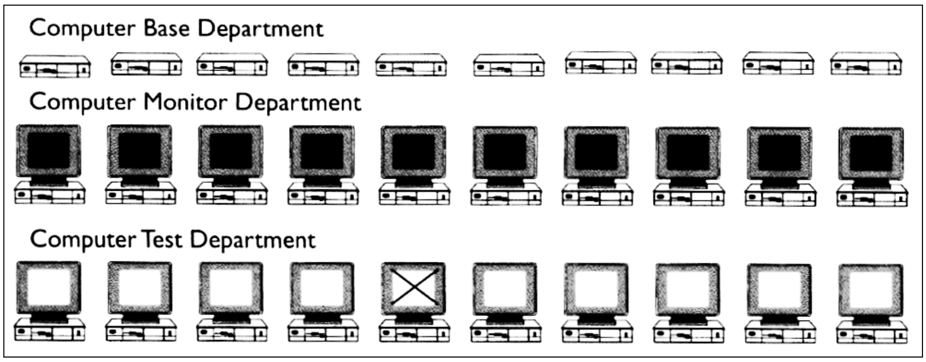


Figure 10.: Batch processing example (Liker, 2004, p. 92)

Figure 10 shows an example of a computer maker, organized into three departments, which produced a batch size of ten units each. Each department needs one minute per unit, which makes ten minutes for a batch of computers per department. Without considering the time for material handling between departments, it takes 30 minutes to make, test and ship the first batch of ten units to the customer. With only three minutes of value-added work, the first computer would be ready to ship after 21 minutes. (Liker, 2004, p. 87-96)

The ideal batch size in lean thinking is always one and processes are physically lined up in a sequence that will produce customer orders in the shortest time. The flow of material would be optimized to move quickly through the factory by creating work cells grouped by products, rather than processes. (Liker, 2004, p. 87-96)

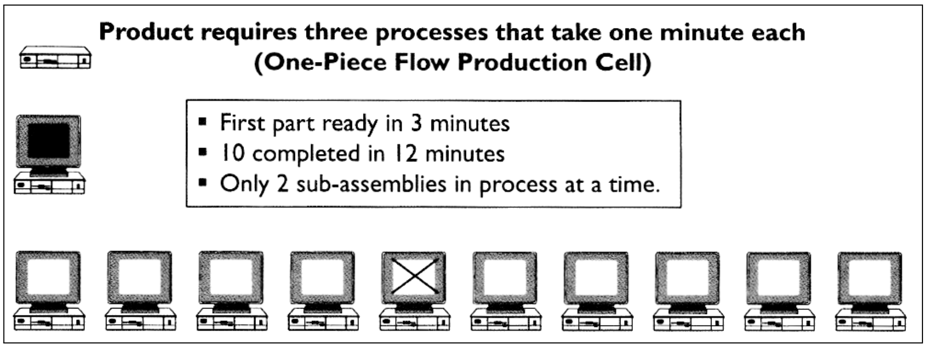


Figure 11.: Continuous flow example (Liker, 2004, p. 93)

The same computer-making process from above organized in a one-piece-flow, illustrated in Figure 11, puts the three processes next to each other in a cell. The operator would not make the next sub-assembly until it is required by the next process step and thereby preventing inventory to be built up between the three operations. As a result the operators take 12 minutes to produce 10 computers, while it takes 30 minutes for the same output in the batch process. This continuous one-piece-flow process reduced the production lead time from 21 minutes to 3 minutes and eliminated inventory and overproduction. (Liker, 2004, p. 87-96)

Both Figure 10 and Figure 11 show a defective computer, marked with an X that failed in the test department. In a large batch production in Figure 10 are at least 21 sub-assemblies in the process that might have the same problem. The continuous flow example in Figure 11, by contrast, only has two other computers as WIP in the system. The defect is found after two minutes of production time. The WIP between operations make it nearly impossible to identify why and when the defect accrued. (Liker, 2004, p. 87-96)

In this sense one-piece flow builds in quality, as every operator inspects and fixes problems in the station before passing the parts on. The defect will be detected very quickly and corrective actions can begin immediately. The production lead time is very short, which makes the process more flexible to react to changes in customer demand and to product a different product mix. In large batch operations productivity is often measured in equipment utilization which leads to overproduction. One-piece-flow creates higher productivity as there is little non-value-added activity like moving material. Additionally the "utilization" of workers becomes visible and the people needed for a certain production rate are easy to calculate. The production of WIP and inventory takes up free capital for investment, as well as floor space. (Liker, 2004, p. 87-96)

2.2.4. Chaku-chaku and one-piece flow production cells

The continuous flow example in Figure 11 is organized in a one-piece flow production cell or manufacturing cell. The operating mode can be "chaku-chaku", which is Japanese and literally translated means "load load". The operator is proceeding from machine to machine, loading a machine with a part from the previous one. The goal of the chaku-chaku method is to implement one-piece flow in combination with decreasing non-value-added tasks. (Womack & Jones, 2003, p. 347f)

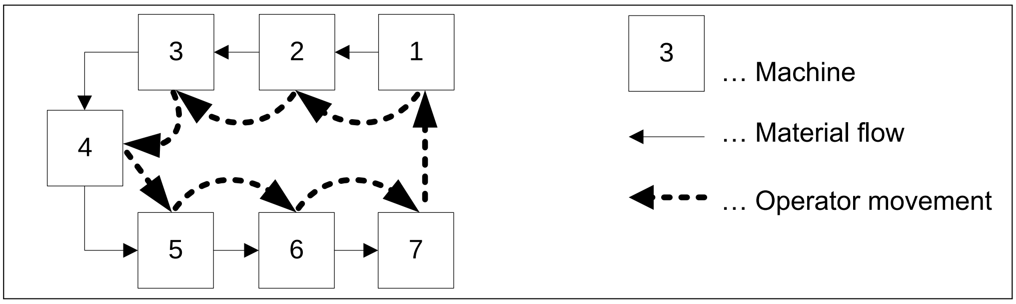


Figure 12.: U-shape manufacturing cell (cf. Rother et al., 2006, p. 49)

A U-shape, shown in Figure 12, is a very efficient layout for a manufacturing cell, because value-adding tasks are close to each other and walking distances can be kept at a minimum. There are more machines or workstations than operators in a manufacturing cell, but the number of operators can vary depending on the demand. Occupational safety and ergonomic workplace design is very important, as the goal of lean processes is to support the operator in performing the value-added tasks. Poor ergonomics can be demotivating and foster waste. (Rother et al., 2006, p. 42-44)

2.2.5. Takt time

The heartbeat of a one-piece-flow process and the rate of customer demand for products produced by one process is the takt time. It is the German word for “rhythm” or “pulse” and often used for assembly processes serving an external customer. (Liker, 2004, p. 94f; Rother, 2010, p. 79 - 82; Ortiz, 2006, p. 45f)

If the customer is buying 9.600 units a month and the effective operating time per shift is 8 hours (480 minutes) for 20 days a month. The production rate or takt time should be 60 seconds. Every process directly or indirectly related should produce at the same pace. The takt time is used to set the pace of the production and is most easily applied in repetitive manufacturing. (Liker, 2004, p. 94f) If the cycle time (actual time to complete a task) of a process is greater than the takt time, additional time is necessary to meet the scheduled production output and a bottleneck is created. *»If the cycle time is less than takt, there will be overproduction or waiting time.«* (Liker & Meier, 2006, p. 136)

The calculation of the takt time is shown in Equation 2.1, which is according to Rother (2010, p. 79) *»calculated by dividing the effective operating time of a process (for example, per shift or day) by the quantity of items customers require from the process in that time period.«*

$$\text{Takt time} = \frac{\text{Effective operating time per shift}}{\text{Quantity required per shift}} \tag{2.1}$$

Effective operating time Effective operating time or effective hours is the available time associated with operators producing products. For the calculation planned downtimes such as breaks, lunch, team meetings, clean-up and planned maintenance need to be considered. Unplanned downtimes and changeover times are variables that should be reduced and are therefore not subtracted. (Rother, 2010, p. 79; Ortiz, 2006, p. 47ff) An example for the calculation of the effective operating time with a total attendance time of 540 Minutes (9 hours) is shown in Table 1.

540 min	Total attendance time
-30 min	Lunch (not paid)
510 min	Paid attendance time
-30 min	Breaks
480 min	Effective operating time

Table 1.: Calculation of effective operating time

2.2.6. Pull systems

In a *pull* system, items are supplied depending on the actual customer demand, rather than items that are pushed by the supplier which are not needed immediately and therefore create a lot of inventory. A company might be willing to pay a little more for an “on-demand” service to receive material and parts as needed. In this case there is some inventory and the replenishment is triggered when parts are used. (Liker, 2004, p. 104-112; Wilson, 2010, p. 51f)

One-piece flow, discussed in Section 2.2.3 is the purest form of pull, giving the customer, which might be the next step in the production process, what, when and in the amount needed. Flow in a one-piece-cell would be a zero-inventory system that is 100% on demand by making one single product for one customer order. Production according to a schedule using a push system would create inventory and would lead to overproduction. The schedule is made in advance, based on projected customer demand, which can change over time. A compromise between the ideal flow and push are small buffers between operations to control the inventory. Parts are replenished when they are used, to create a connection between production and customer demand. (Liker, 2004, p. 104-112; Gerberich, 2011, p. 128ff)

A simple way to signal parts or material were used in an assembly are empty bins or empty carts – called *Kanban*. “Kanban” is Japanese and means card or sign and is used as a signal the need to refill parts. A Kanban contains detailed information regarding the part, such as quantity and location. Even today simple, effective and highly visual kanban systems are used to manage and ensure the flow of materials in a just-in-time production. (Liker, 2004, p. 104-112; Gerberich, 2011, p. 128ff; Wilson, 2010, p. 48f)

An example of a pull system is the fuel tank of a car, the replenishment is triggered by the gas gauge approaching empty and refueling gas at the gas station. Another example is stock of household items, once the inventory reaches a low point stock is refilled with a trip to the supermarket.
Special or single-use items, usually of higher value cannot be replenished based on a pull system. As there is no immediate use for it, a schedule to purchase is created. But for most situations kanban/pull systems work better than a schedule system. As the system depends on small inventories or buffers, the goal is to eliminate these buffers and move to a true one-piece-flow whenever possible. (Liker, 2004, p. 104-112)

Pure flow is not possible when the cycle times are very different or processes are too far apart. In this case pull systems are the next best choice. For example stamping of panels for a car body is a much faster process than the takt times in a car assembly factory, for example one second for stamping a panel compared to 60s takt time in the assembly operation. Putting these two processes into a one-piece-flow is not practical and a pull system is used instead. After a defined number of steel panels used in the assembly factory, a kanban goes to the stamping press and triggers the replenishment, illustrated in Figure 13. (Liker, 2004, p. 104-112)

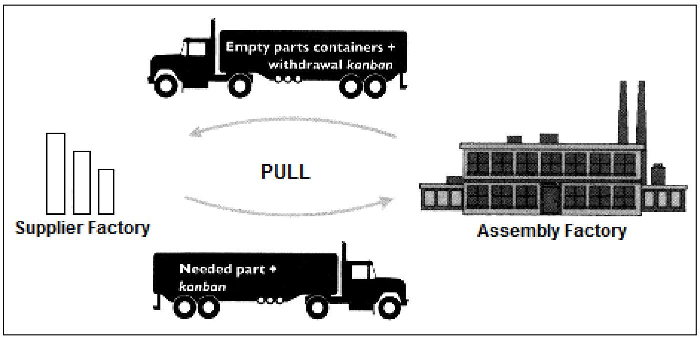


Figure 13.: Example for a pull system (cf. Liker, 2004, p. 109)

The kanban system in an assembly line works similarly. The workers put a kanban – card or empty bin – on a defined spot and a material handler picks up the kanban on a timed route and replenishes the used parts. The major benefits of a kanban are the simplicity of the system and it forces improvement in the production. Because it is an organized system of inventory buffers and inventory is waste according to lean thinking, the goal is the get rid of kanban. (Liker, 2004, p. 104-112)

2.2.7. Leveled production

To be able to apply pull systems and balance assembly lines, it is absolutely necessary to level the production output to keep it more or less constant over a month. This production leveling might require front-loading or postponing of orders and some customers will have to wait for a short period of time. It the production output varies from day to day, it does not make sense to apply assembly line balancing or establish standard work procedures. (Liker, 2004, p. 113ff)

In a build-to-order model the production just makes what and when the customer wants it, which is the ultimate lean solution. Unfortunately, the orders often vary significantly because customers are not predictable. Building a product as ordered means there might be high quantities required one week, stressing people and equipment and maybe paying overtime, and the next week people might have little work and equipment might be underutilized. Also piles of inventory are necessary to satisfy the demand for each item the customer might order. (Liker, 2004, p. 113ff)

It is simply not possible to run a lean operation this way. The leanest approach to give customers better service and quality is a leveled production schedule and not a strict “hurry up, slow down” build-to-order production. By accumulating orders and leveling out the schedule it is possible to keep a steady pace of the operation, which reduces production lead times and inventory and results in a greater overall customer satisfaction. (Liker, 2004, p. 113ff)

The number one focus of most lean manufacturing efforts is the elimination of *muda* (waste). To make lean work, it is important to not exclusively target the eight wastes, but tackle the “elimination of *Muda, Muri, and Mura*, illustrated in Figure 14. (Liker, 2004, p. 113ff)

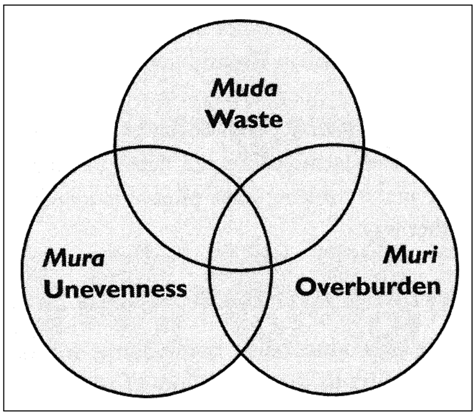


Figure 14.: Muda, muri, and mura (Liker, 2004, p. 115)

Liker (2004, p. 114f) and Gerberich (2011, p. 122f) describe *Muda, Muri, and Mura* as follows:

- **Muda – Non-value-added.** Muda includes the eight wastes discussed in Section 2.2.1 such as extra movement, any type of waiting, excess inventory and everything lengthening lead times.

- **Muri – Overburdening people or equipment.** Muri includes pushing people or machines beyond natural limits, which may result in safety or quality issues as well as equipment breakdown or defects. For example, requiring operators to work at a higher pace, with more effort and for a longer period than appropriate management would allow (LeanEnterpriseInstitute et al., 2008, p. 63).

- **Mura – Unevenness.** Mura is the unevenness of the irregular production schedule or fluctuation of production volumes, due to downtime or missing parts. This unevenness means sometimes there is more work than people and equipment can handle and at other times there is not enough work. Mura leads to muda, because unevenness in the production makes it necessary to have equipment, machines and people on hand for the highest production level – even if the demand is lower.

Applying lean thinking by only focusing on the elimination of muda – reduce inventory in the production system, balance the work content and reduce the number of people from the system - will most likely fail. Spikes in customer demand will force people and equipment to handle more work than they efficiently can. Identifying and eliminating waste is easy. Creating “evenness” and stabilizing the system is more difficult on the way to a true balances lean workflow. (Liker, 2004, p. 115) Hence the first step is the elimination of *mura*, which can be reached with the concept of *heijunka*. This builds the foundation for further eliminating *muri* and *muda*. (Gerberich, 2011, p. 123)

Heijunka. The concept of *heijunka* is leveling the production by both volume and product mix over a fixed period of time. (LeanEnterpriseInstitute et al., 2008, p. 28) The products are not scheduled according to the actual sequence of customer orders, but the orders in a period are leveled to get a similar volume and mix for each day. With the actual customer demand it is necessary to determine the pattern of volume and mix in order to smooth the schedule for every day and create a level production sequence. This is referred to as leveled, mixed-model production, which spreads the different levels of volume and product types by leveling the demand and mixing up the production. (Liker, 2004, p. 116-125) In this way it is possible to avoid batching with small inventories, and therefore enables efficient production to meet the customer demands. (LeanEnterpriseInstitute et al., 2008, p. 28)

An unleveled schedule leads to an unbalanced use of resources. Different types of products require different labor time. This system contains a high potential for *muda* and *muri*. Perhaps the most serious problem of an unleveled production is the placement of an uneven demand on the upstream processes. The suppliers will prepare for possible scenarios and keep high levels of inventory to supply demanded parts and material. This behavior can multiply backward (upstream) through the supply chain and create the so-called “bullwhip-effect”. Small changes in the production schedule of the assembly plant can result in increasing amounts of inventory at each stage of the supply chain back from the final customer. (Liker, 2004, p. 116-125)

This mass production approach with large lots of items (batches) processes and moves the items to the next process. (LeanEnterpriseInstitute et al., 2008, p. 5) The goal of a batch-processing mode of a traditional, unleveled production is to achieve economies of scale effects for each individual price of equipment. In order to keep changeover times and related costs low, it is logical to build large batches of one product before changing to another one. This traditional approach does not allow for the concept of *heijunka*. (Liker, 2004, p. 116-125)

The solution can be a production line capable of handling multiple products without changeover time – called a mixed-model assembly line. Figure 15 shows a leveled production schedule of a mixed-model engine assembly line with a repeating sequence of three engines sizes, which matches the product mix ordered by the customer. (Liker, 2004, p. 116-125)

The benefits of heijunka are flexibility to produce what customers want and when they want it and at the same time reduce the risk of unsold goods. Due to the leveled production it is possible to balance the use of labor and machines. In the example shown in Figure 15 some engines require more work, some require less. As long as products with a high amount of work content are not followed by another one, the workers will be able to handle it. The demand for the just-in-time system for the upstream process will be smoothed by the even schedule. The suppliers will receive a stable level of orders, which allows them to reduce inventory buffers and pass on cost savings downstream. (Liker, 2004, p. 116-125; Gerberich, 2011, p. 136)

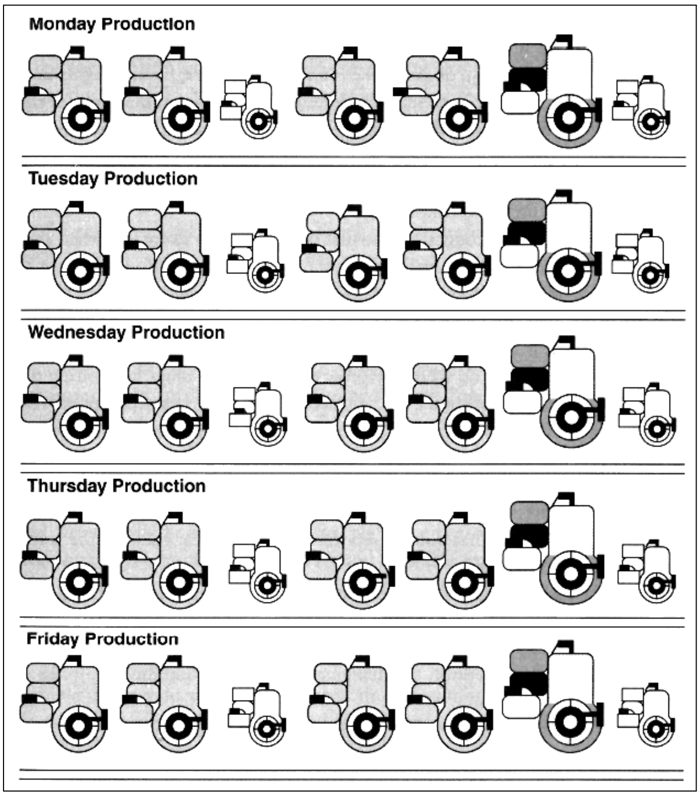


Figure 15.: Leveled mixed model production (Liker, 2004, p. 117)

Heijunka is essential to achieve the lean benefits of continuous flow. Eliminating *muda* is only a third on the way of implementing flow, which makes eliminating *muri* and smoothing *mura* equally important. (Liker, 2004, p. 116-125) These elements of modern lean production systems only work together in a system. This is the same compared to an engine, with one element missing the system does not work.

2.3. Assembly lines

The first assembly line was built for the production of the Ford Model T. Taiichi Ohno further developed the assembly line concept and implemented important elements from eliminating waste to a leveled production schedule, discussed in Section 2.2. These elements are the foundation for modern assembly lines.

Scholl (1999, p. 2f) defines assembly lines as *flow-line production systems* used to produce a high quantity of standardized products, which consist of a number of workstations along the material flow. An example of a gearbox assembly line is shown in Figure 16. The gearboxes are steadily moved form station to station along the material flow down the conveyor belt. The total work necessary is divided and distributed among the workstations along the assembly line.

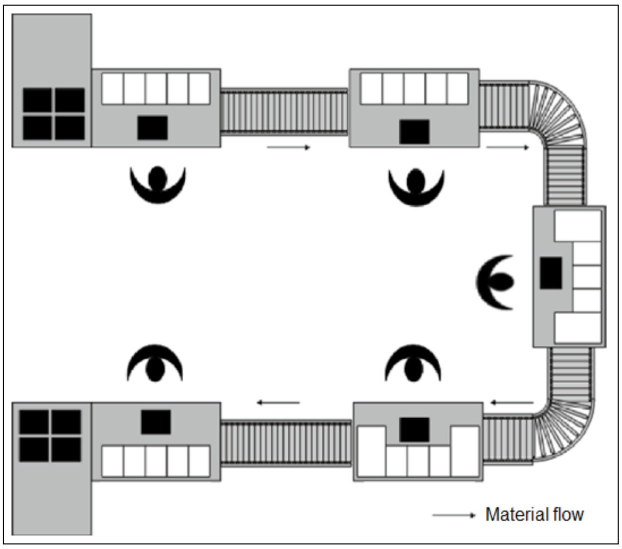


Figure 16.: Layout of a gearbox assembly line (Lotter & Wiendahl, 2012, p. 91)

A flow-line production system is arranged according to the sequence of operations and therefore has a *process-oriented* layout, which well suited to large scale series production. Whereas a job shop production system is mainly used for small batch production. The organization is *functional (job-oriented)* and for that reason the operations are spatially combined in workshops. (Scholl, 1999, p. 1)

The main **advantages** of flow-line systems are high capital utilization, small throughput times, low in-process inventories, simple control of material flow, small requirement of space and due to strict division of labor, less skilled operators are needed that require less training. **Disadvantages** which may restrict the application are high capital investments, monotonous job contents leading to low job satisfaction and inflexibility of the system due to high degree of specialization. Also maintenance and repairs become more critical due to the influence of breakdowns on the complete system and the need for in-process quality control. (Scholl, 1999, p. 2)

Pre-conditions such as standardized products, high volume production, stable product demands, and continuous material supply are required for a successful flow-line production system. (Scholl, 1999, p. 2)

2.3.1. Basic terms for assembly lines

This section defines necessary terms in respect to assembly lines and the goals of the thesis based on Scholl (1999, p. 4f).

Assembly. Is defined as the process of collecting and fitting together different parts to create a finished product. The parts used can either be sourced (purchased) or pre-assembled in-house.

Operation. An operation or task is a piece of the total work content of a finished product in an assembly process. An operation cannot be split into smaller parts without adding unnecessary additional work for example, reaching for a screw, grasping it and putting it into a thread. The operation time is thus the time necessary to perform an operation and can be determined for example with systems of predetermined times, see Section 2.4.3.

Operator. A human operator performs operations manually, using tools or semi-automatic machines.

Workstation. A workstation is a section of an assembly line where a certain amount of work is performed. Workstations can be mainly characterized by its work content and equipment and be divided into a manual operation performed by a human operator, or automated stations.

Precedence constraints. The order of which operations are performed can be restricted due to assembly sequence or technological reasons. It can be illustrated by using a precedence diagram (precedence graph) which contains nodes for all operations visualizing the required order of the performance of these operations.

Takt time. Takt time is the heartbeat of a one-piece-flow process and sets the pace of an assembly line. It represents the rate of customer demand. (cf. Section 2.2.5)

Cycle time. The Cycle time (C/T) is the required time it takes an operator to finish the tasks at a workstation (Rother & Shook, 2003, p.17). From the moment the workpiece arrives at the work station until all operations are completed (Törenli, 2009, p. 22).

Idle time. It defines the period of time after completing the tasks in which the operator has to wait until the next workpiece is delivered to the workstation. It is the difference between takt time and cycle time at a station, also called waiting time (waste). (Törenli, 2009, p. 23) Figure 17 illustrates the relation between takt time, cycle time and ilde time.

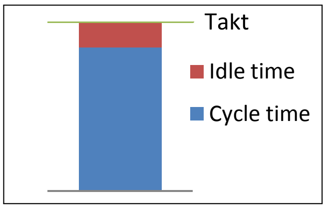


Figure 17.: Relation between takt time, cycle time and idle time

2.3.2. Types of assembly lines

Descriptions of the types of assembly lines can be found in work of Naveen & Dalgobind (2013, p. 2f), Törenli (2009, p. 14f) and Breginsk et al. (2013, p. 1f). These are all based on the three main types of assembly lines defined by Scholl (1999), which are single model, mixed model and multi model assembly lines, illustrated in Figure 18.

In a *single model assembly line* the work content at a station is the same of every product assembled. This enables a profitable utilization of the assembly line at a high level production. (Naveen & Dalgobind, 2013, p. 2)

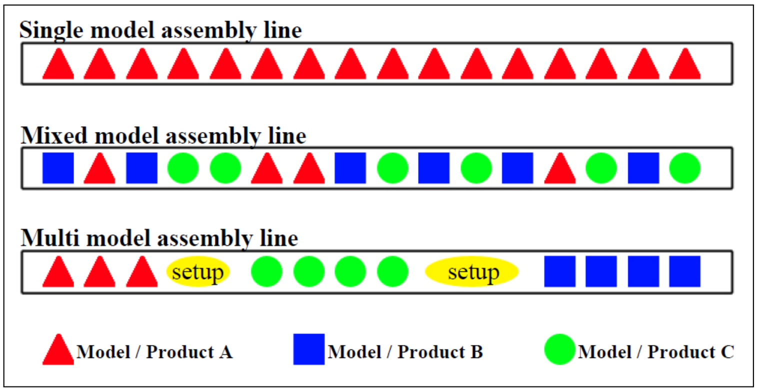


Figure 18.: Different types of line assembly lines (Scholl, 1999, p. 7)

In a *mixed model assembly line* variants of a single product (model) or similar products are assembled without the need to setup, or small enough to neglect the setup time. Operations for different variants or products are similar and undergo similar processes, but the operating times may be different at the workstations. Different variants can be assembled without any need for modification at the line, but there may be constraints for the production scheduling, the sequence of the products, because of different cycle times. (Naveen & Dalgobind, 2013, p. 2; Törenli, 2009, p. 14)

The most complex among these assembly lines is the *multi model assembly line*. There are significant differences in the assembly of each variant of the product and requires a setup. In order to minimize inefficiency of the setup times, the assembly is arranged in batches. (Törenli, 2009, p. 15; Breginsk et al., 2013, p. 2)

2.3.3. Assembly line balancing

Assembly line balancing is the distribution of the total workload of a product among the workstations to reduce operator idle times. The main objectives are to minimize the number of workstations or maximize the production rate of the assembly line, which on the bottom line leads to an increase in productivity. (Naveen & Dalgobind, 2013, p. 2; Törenli, 2009, p. 18) Assembly line balancing is a technique with significant importance in lean manufacturing systems. (Naveen & Dalgobind, 2013, p. 2) The result of a well-balanced assembly line is the reduction of waste, such as operator idleness, stock, defects and also decreases the production cost per unit. (Breginsk et al., 2013, p. 1)

It is important to consider all products produced in a mixed model assembly line. The weighted average of the times of the different products can be used and therefore line balancing is no different than to single model lines. (Breginsk et al., 2013, p. 1; Ortiz, 2006, p. 99) The losses due to variants increase with increasing variants produced. At workstations with a fixed number of operators the variant losses will be higher for more complex models. (Törenli, 2009, p. 20)

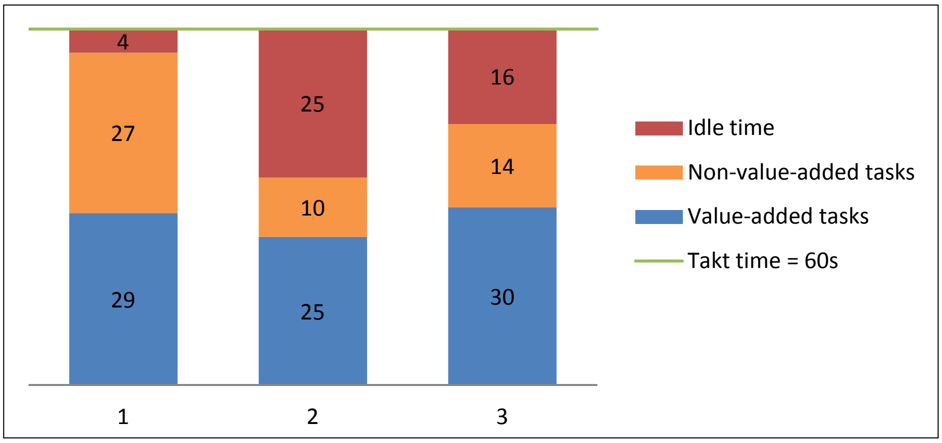


Figure 19.: Assembly line balance

The process of line balancing starts with the initial situation and the differentiation of value-added and non-value-added tasks. The three workstations (1, 2, 3), with a takt time of 60 seconds, in the example shown in Figure 19, have a high idle time and a high content of non-value-added tasks. The goal is to minimize non-value-added tasks as well as the idle time over the assembly line, as both of them are a type of waste. Therefore the next step is to eliminate or reduce non-value-added tasks which are not directly linked to perform a value-added task, walking to get material. As shown in Figure 20, the time of the non-value-added tasks was converted into idle time. (Takeda, 2002, p. 111) As Naveen & Dalgobind (2013, p. 5) mention, one way to reduce waiting time is paralleling of tasks.

The total work content of value-added and non-value-added tasks was decreased to 112 seconds and can now be distributed over two workstations, leading in a reduction of one workstation, shown in Figure 21. (Takeda, 2002, p. 111)

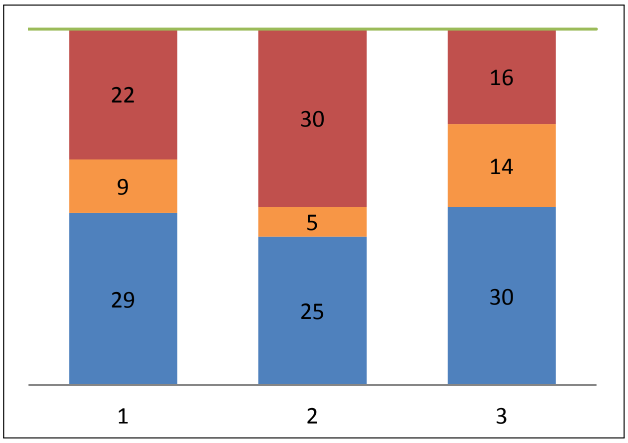


Figure 20.: Reduction of non-value-added tasks

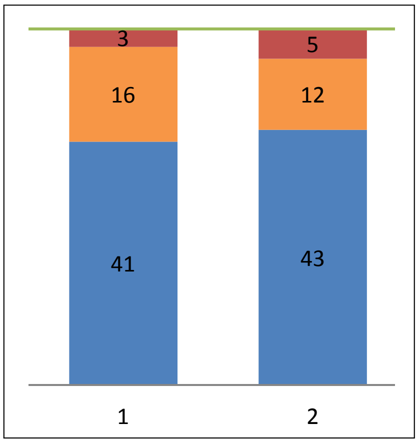


Figure 21.: Redistribution of work content

Two types of line balancing. Rother et al. (2006) differentiate between two types of distribution of work contents over the workstations. The conventional way of *equal distribution*, illustrated in Figure 22, over the workstations. The cycle time is the same, but the operators do not work at full capacity. The equal distribution follows the need for fairness, but tends to equally distribute waiting times over the workstations (waste), which makes it more difficult to identify potential for improvement. Figure 23 shows the *lean oriented distribution* of tasks to full capacity during a takt. Waste in form of waiting time is concentrated at one workstation and makes hidden waste clearer and more visible. (Rother et al., 2006, p. 53f)

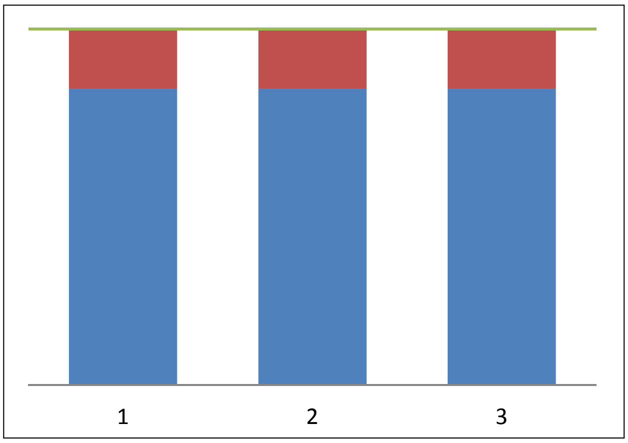


Figure 22.: Equal distribution (cf. Rother et al., 2006, p. 54)

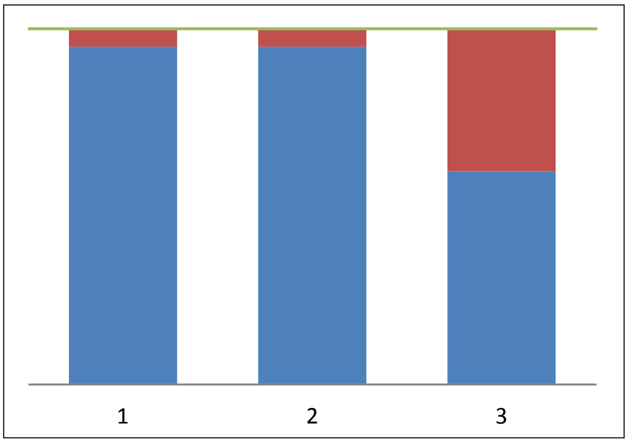


Figure 23.: Lean oriented distribution (cf. Rother et al., 2006, p. 54)

Ortiz (2006) suggests a *85% rule* for designing and balancing an assebmly line. Operators are not able to work 100% of the shift at optimum rate. If they do so, they will create more defects, become less productive during a shift, and eventually develop health related issues. *»A realistic operator load of 85% allows for a smooth and efficient flow of product, without jeopardizing quality, productivity, or health.«* (Ortiz, 2006, p. 49)

2.4. Industrial engineering for assembly lines

Frederic W. Taylor's works and organization of manufacturing operations marks the beginning of Industrial Engineering (IE). (Smith & Hawkins, 2004, p. 2; REFA, 1984, p. 25) Although the term *industrial engineering* was not used in his work. (Martin-Vega, 2001, p. 1.5)

The definition of industrial engineering according to the American Institute of Industrial engineers is:

> *Industrial engineering is concerned with the design, improvement, and installation of integrated systems of men, materials, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical and social sciences together with the principles and methods of engineering analysis and design to specify, predict, and evaluate the results to be obtained from such systems. (Martin-Vega, 2001, p. 1.11)*

Thus typical tasks of industrial engineers are rationalization of material flow, layout planning, quality assurance, value stream analysis and implementation of standards. The three main task areas for an industrial engineer as defined by REFA (1984, p. 37), are:

- testing and implementing new methods of rationalization,
- coordinating between different departments, and
- conducting projects beyond departments.

The work of industrial engineers has to consider social human needs and is in general, evaluated with respect to economic aspects (REFA, 1984, p. 42). A successful industrial engineer considers at least the three critical criteria of quality, time and cost simultaneously (Hicks, 2001, p. 1.85f). The rationalization measures as part of industrial engineering work leads to a direct increase in productivity, which increases economic efficiency and profitability. The venture's success emerges not from a single measure, but from interactions between lots of measures. (REFA, 1984, p. 46)

The goal of this thesis is to reduce the processing time, and thus increase productivity by utilizing the potential in the assembly line. This section elaborates on the theoretical background for industrial engineering part of this thesis.

2.4.1. Productivity

Productivity is a ratio of performed output to input. From the point of work-studies the so called *labor productivity* is more important and according to REFA (1984, p.43) defined as:

$$\text{Labor productivity} = \frac{\text{Quantitative performance}}{\text{Quantitative labor input}} \tag{2.2}$$

Labor productivity can be improved by manufacturing more units with less labor input. The labor productivity in relation to quantity is the most used ratio for proof of success of a rationalization measure. REFA (1984, p.43) describes following example:

The production output of an operation is 720 units during one shift with 12 operators. The labor productivity amounts to 60 units per shift and operator, see Calculation 2.3.

$$\text{Labor productivity} = \frac{\text{Quantitative performance}}{\text{Quantitative labor input}} = \frac{720}{12} = 60 \text{ units} \tag{2.3}$$

By implementing performance-related payment the output per shift with the same amount of operators should increase to 864 units (Calculation 2.4).

$$\text{Labor productivity after implementing performance-related payment} = \frac{864}{12} = 72 \text{ units} \tag{2.4}$$

The focus for improvement should not be on working faster, but on working smarter and more efficiently, with less resources. Ortiz (2006, p. 42) mentions that a goal to increase labor productivity should be reducing the number of operators in the assembly line.

2.4.2. Ergonomics and workplace design

The science of ergonomics is a tool for productivity and quality enhancements, that can be applied in any work environment. It provides industrial engineers with knowledge of capabilities and the limitations of humans and risk factors in relation to manufacturing operations.(Roth, 2001, p. 6.9)

»Ergonomics literally means the study of work.« (Joseph et al., 2001, p. 6.55) It is also called human engineering. Ergonomics deals with the human response and interaction to the work environment, tools and equipment, work methods or organization. It is important for an industrial

engineer to understand the human responses in a work environment to prevent improper workplace design and potential injury or illness. The objective is to fit the work or task to the employees. (Joseph et al., 2001, p. 6.55; Roth, 2001, p. 6.9; Pheasant, 2003, p. 4f; REFA, 1984, p. 125)

Properly designed workplaces, tools, equipment and facilities can reduce occupational injuries, sickness, absenteeism and can furthermore improve productivity, product quality and motivation. (Joseph et al., 2001, p. 6.56) The thesis will focus mainly on economical workplace design in respect to productivity and performance. The environmental influences such as climate, lighting, noise, mechanical vibrations, color and dust will not be further described.

The total workload and therefore the recovery time, depends on the heaviness of the burden, body posture, frequency and length of activity without a break. According to DIN 33 400 strain is the influence of work and environment on humans and stress is an effect of work on an individual human. Stress can vary among human beings, whereas strain is always the same. (REFA, 1984, p. 159-161)

Predominantly physical work. REFA (1984, p. 163) classifies physical labor regarding four different types of muscular activity:

- Static body posture
- Static holding activity
- Heavy dynamic activity
- Monotonous dynamic activity

Static muscular activities without movement over a longer period of time, such as overhead welding, places the muscle under tension. Due to the contraction of the muscles, the blood supply is significantly limited. This includes sustaining a certain body posture for example, sitting without a backrest or standing.

Dynamic muscular activities help increase the blood supply by alternating contraction and relaxation of the blood vessels. Due to this reason, static activities are more exhausting than dynamic activities with sufficient blood supply. Inconvenient and unfavorable body postures can lead to long term health issues, therefore workplace design must prevent pure static activities. (REFA, 1984, p. 163f) Figure 24 illustrates the difference in blood supply and requirements for rest, dynamic and static activities.

Bosch Rexroth AG (2012, p. 6) suggests to promote dynamic activities that supply a sufficient amount of oxygen to the muscles. Job rotation can also increase endurance and performance of operators by varying physical exertion. To minimize physical exertion, it is beneficial to use lifting aids or rollable platforms.

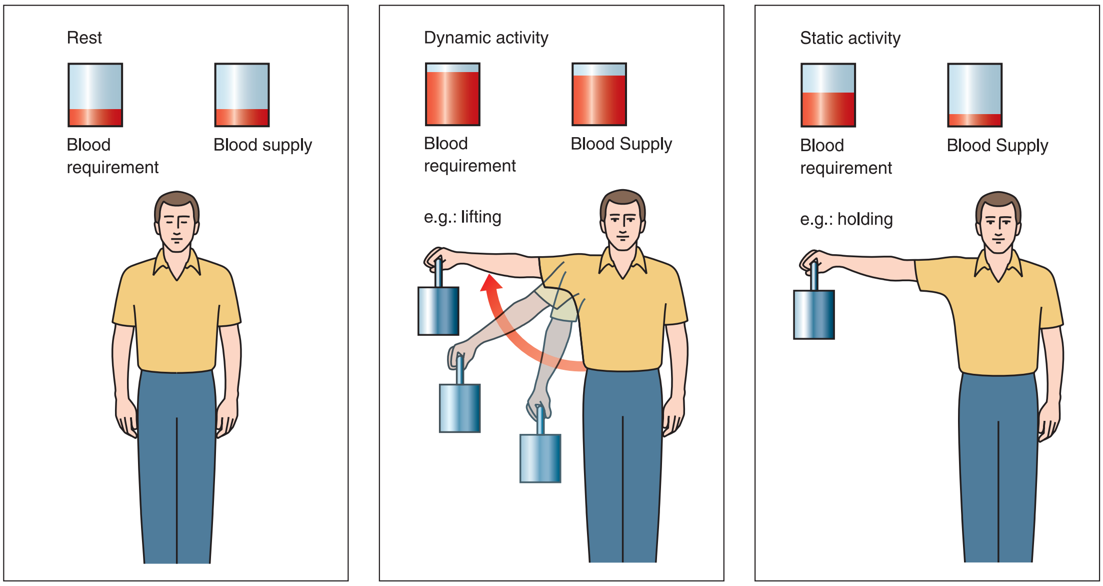


Figure 24.: Blood supply of muscles during different activities (Bosch Rexroth AG, 2004, p.6)

Principles for a favorable use of muscular activities according to REFA (1984, p. 170) are:

- Affordable forces should not exceed a certain amount of the maximum force of the affected group of muscles.
- The maximum force depends on the direction in relation to the operator. Directions longitudinal to the body are more favorable than parallel directions.
- Avoid static muscle activities.
- Avoid distribution of forces with the body.

Working height. Anthropometry is part of the human sciences and ergonomics which deals with measurements of body size, shape, strength and working capacity (Pheasant, 2003, p. 6). The adaption and adjustment of the workplace requires theses metrics of the human body for the design of workstations (REFA, 1985, p. 142). Anthropometry supports workplace design with measurements of operators in respect to shape, measurements and the relative arrangement of the single elements of workstations (Schlick et al., 2010, p. 1028).

Workstations, especially manual workstations, must accommodate a wide range of body heights in order to cover the largest percentage of the population. (Bosch Rexroth AG, 2012, p. 4) The adjustment of working heights for standing workstations is much more difficult than for seated workstations, as the difference between small women and tall men is larger. (REFA, 1984, p. 198) Figure 25 illustrates the difference of optimum reach, clearance and range of vision for a standing position in two different body heights - 1500mm and 1900mm.

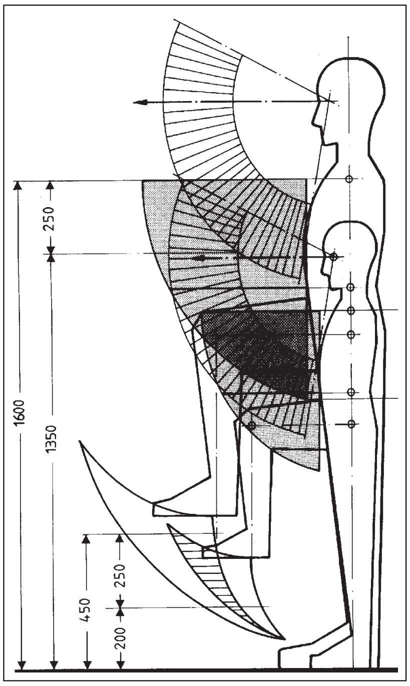


Figure 25.: Optimum reach, clearance and range of vision [units in mm] (Schlick et al., 2010, p. 1038)

One way to deal with the adjustment of working heights, is to use tables with flexible working heights shown in Figure 26. However, in general table and equipment heights are not adjustable in assembly lines. This would favor a design for the tallest men and the use of height adjustable platforms. (REFA, 1984, p. 198)

Reach zones and parts presentation. For an ergonomic design of the reach zones, all bins, containers, tools and equipment should be easily accessible and arranged according to the movement of assembly. (Bosch Rexroth AG, 2004, p. 4)

Figure 27 illustrates the reach zones for a woman of medium height (1660mm tall). These reach zones are characterized into three areas. Area C represents the optimum working with both hands, as both hands are in the operators range of vision. This area is favorable for inspection an coordination activities and mostly uses smaller muscle groups. Area B is the extended or larger reach zone for for activities with one hand. Movements include upper and lower arms, as well as use of the shoulder and rotation of the torso. Area A is for occasional handling and involves movements of shoulder and torso. (Bosch Rexroth AG, 2012, p. 8)

The reach zones should especially considered the efficient parts presentation to avoid unnecessary movements and thus avoid waste. Containers and bins should be in direct reach of the operators and should enable a flowing motion when they are moved. An optimum parts presentation can

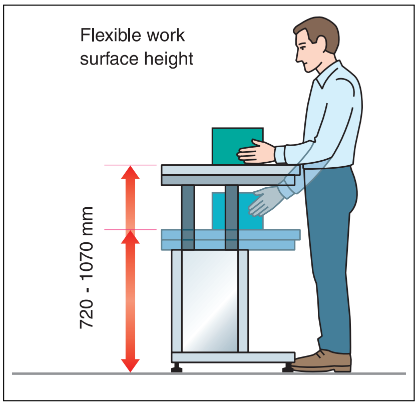


Figure 26.: Flexible working height (Bosch Rexroth AG, 2004, p.3)

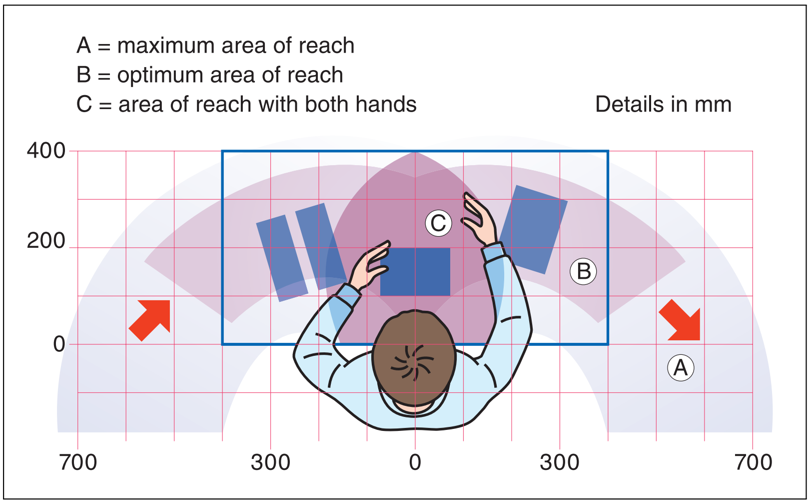


Figure 27.: Reach zones for a woman of medium height (Bosch Rexroth AG, 2004, p. 4)

significantly reduce the time for parts supply and removal, so operators can focus on productive assembly work. (Bosch Rexroth AG, 2012, p. 9)

Pheasant (2003, p. 46) describes principles of rational workspace layout, which are applicable in a large variety of design aspects:

- *Importance principle*: most important items should be most accessible
- *Frequency-of-use principle*: most frequently used items should be most accessible
- *Function principle*: items with similar functions should be grouped together
- *Sequence-of-use principle*: items which are commonly used in sequence, should be arranged in this sequence

The scientific background for the features of workplace design in Chapter 3, is based on the three aspects of physical work, in terms of static and dynamic activities, the working height, and reach zones which incorporate how parts are presented. Only by creating efficient and optimized workstations, it is possible to set the boundary conditions for productive work.

2.4.3. Methods time measurement

Methods Time Measurement (MTM) is one of the common systems of predetermined times amongst Work Factor (WF), and Maynard Operations Sequence Technique (MOST). (Lotter & Wiendahl, 2012, p. 100) The functionality of predetermined systems will be explained using the example of MTM, as it is the foundation for the industrial engineering at BMW and will be based on the work of Aft (2001, p. 5.3 - 5.10).

MTM is a motion-based predetermined time system which provides standard times for human motion in different categories. An estimate of the standard time for performing a specific task can be determined by analyzing the sequence of human motions according to predetermined times and not by measurement or direct observation (Hicks, 2001, p. 1.88).

> *The* ***standard time*** *is the time required by an average skilled operator, working at a normal pace, to perform a specified task using a prescribed method, allowing time for personal needs, fatigue, and delay. (Aft, 2001, p. 5.4)*

An *average skilled worker* is neither best nor worst, but someone with training in the job who can consistently perform the job during the entire workday. *Normal pace* is neither too fast nor too slow, in a way the worker can perform the rate of work during the entire workday. The worker will not always perform at the same pace, thus the normal pace represents the pace an average worker can maintain long term. The *prescribed method* is another key part of the definition of standard time. The standard work instructions describe how to correctly perform the defined task, including the times required and statements concerning quality of the work. To balance personal needs, fatigue and delay, an *allowance* must be taken into account in the standard times.

These standard times provide essential information for the success of the organization such as data for production scheduling, line balancing, staffing, materials requirement planning and related costs. Engineered standard times also provide a tool to precisely manage productivity (Sakamoto, 2010, p. 122). The MTM-1 rating system is based on four factors: skill, effort, consistency and performance. According to Aft (2001), MTM is the most frequently used of all predetermined time systems.

In MTM-1 the manual operations are broken down into the required basic motions and relate each operation to a predetermined standard time. The fundamental motions of MTM-1 are:

- Reach
- Move
- Turn
- Position
- Grasp
- Release
- Disengage
- Eye time
- Body motion

Furthermore, MTM introduces a new Time Measurement Unit (TMU) and is assigned a unit value of 0,00001 hours equal to 1 TMU,shown in Table 2.

1 TMU	=	0,00001	hour	1 hour	=	100000 TMU
	=	0,0006	minute	1 minute	=	1666,7 TMU
	=	0,036	seconds	1 second	=	278 TMU

Table 2.: Time Measurement Unit (TMU)

2.4.4. Standard data

Standard data is developed from one time-measurement technique to reach consistency in estimating target time values for all manual work. (Ostwald & Miller, 2001, 3.82) This section will further be based on the work of Connors (2001, p. 5.41 - 5.72), which is the theoretical foundation of the BMW standard data.

The practical definition of standard data, useful for most predetermined time systems such as MTM-1, is according to Connors (2001):

> *Standard data is work measurement data that is built up, using a work measurement technique, into useful, well-defined, and easily applied building blocks. These building blocks will be structured and defined to a level that is most suitable for the application.*

The development of well-defined standard data requires investment in structure and design definition and can result in many benefits for industrial engineering and production management. The standard data is quickly applicable to different operations and provides increased consistency, between industrial engineering and over multiple facilities and locations. This enables easy comparison and benchmarking of operations. Understanding and acceptance can also be improved with the common set of data. Whereas standard data covers a variety of situations, detailed descriptions may not exist for each possible application.

A set of building blocks provided by the standard data can be extensively used throughout the operation. This building block concept (see Figure 28) is essential for the standard data development.

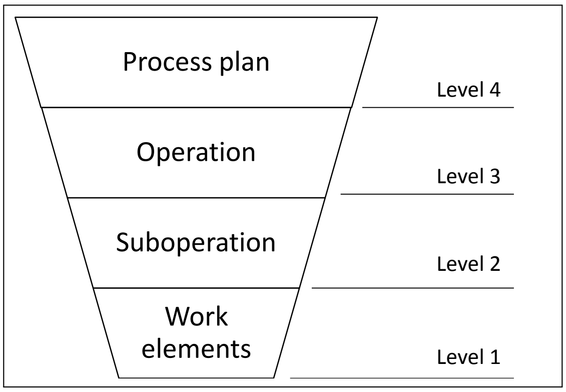


Figure 28.: Building blocks concept (cf. Connors, 2001, p. 5.45)

At the lowest level of the building block concept is the basic work elements such as motion patterns in MTM-1. Level 2 represents sub-operation data and it *»is typically composed of a sequence of one or several fundamental motions and machine/process activities.«* The operational level, level 3, is built up from lower-level data, which is specific to machining operations. The highest level of this example is level 4, with very specific and unique data. An example for level 4 is a work plan for manufacturing. (Connors, 2001, p. 5.46f)

2.4.5. Time per unit as allowed time for men

This section elaborates on the time per unit according to REFA (1978, p. 44-52). The time per unit structure partly builds on the standard times determined with MTM and is important for the understanding of the processing time in Chapter 3.

The structure of *time per unit* t_e is shown in Figure 29 and is the allowed time for a worker to complete a process. With a base output unit of 1, the time per unit is:

$$t_e = t_g + t_{er} + t_v \tag{2.5}$$

The *basic time* t_g is the sum of all target times required by the worker for completing one unit of output and consists of activity time t_t and waiting time t_w:

$$t_g = t_t + t_w \tag{2.6}$$

The *activity time* t_t is the sum of all target times required to complete one unit of output structured into *main activities (MH)* and *ancillary activities (MN)*. It can also be appropriate to divide t_t into *influenceable activity time* t_{tb} and *non-influenceable activity time* t_{tu}. In this case t_{tb} depends on the human performance, whereas t_{tu} cannot be influenced by a worker for example, the process time of a machine.

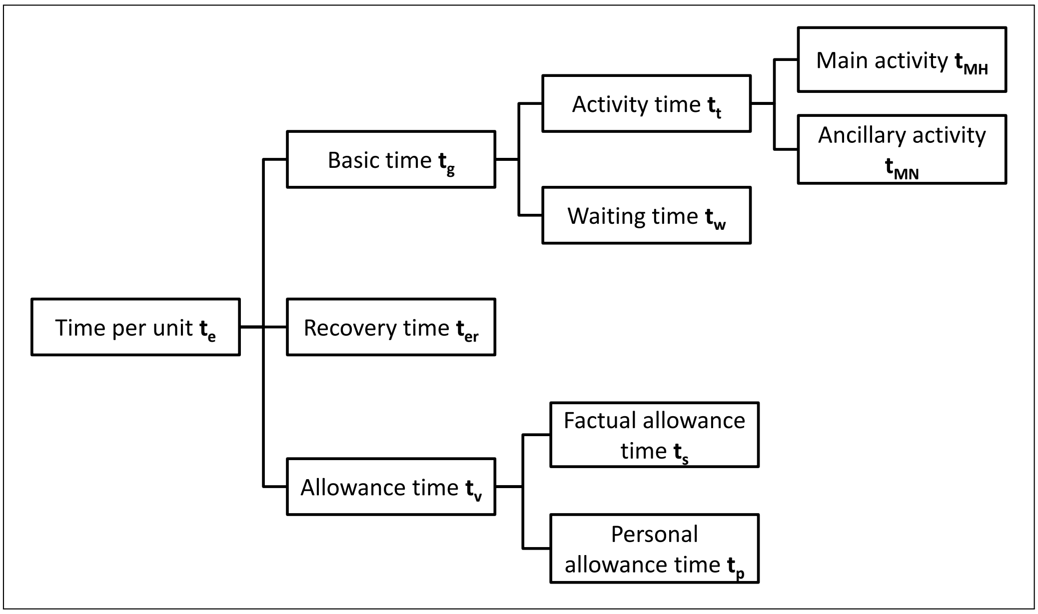


Figure 29.: Time per unit structure related to men (cf. REFA, 1978, p. 47)

The *waiting time* t_w is the sum of all target times related to process interruptions. The *recovery time* t_{er} is the sum of all target times for the recovery of the worker in reference to one unit of output.

The *allowance time* t_w is the sum of all target times of additional processes necessary, related to men in reference to one unit of output. The allowance time is divided into *factual related allowance time* t_s, which includes additional activities and disturbance related interruptions, and *personal related allowance time* t_p, which is related to personal work interruptions. If the the allowance time is specified as a percentage z_v, the calculation as in Equation 2.7.

$$t_e = \frac{z_v}{100} \cdot t_g \quad \text{or} \quad \frac{z_s + z_p}{100} \cdot t_g \tag{2.7}$$

2.5. Summary

The elements of lean production systems, such as one-piece flow, pull and leveled production, described in this chapter are the foundation of assembly lines. The takt time is the hear beat and a central figure of the mixed model assembly line of this thesis. The industrial engineering tools MTM and standard data build the basis for the BMW standard data. This is used to calculate the predetermined times for the operations necessary to assemble the engines. In addition the work on ergonomics is incorporated in this thesis to efficiently arrange the workplaces. The time per unit structure is important for the productivity monitoring, which is via the processing time per engine.

3. Project at BMW

This chapter describes the practical part about the assembly line B/G/E of the new generation of modular kit engines for four- and six-cylinder in-line petrol engines at BMW in Steyr. The following sections of Chapter 3.1 outline the basis for this thesis, including the detailed target definition. Chapter 3.2 describes the specific tools and methods used to reach the defined goals. Chapters 3.3 to 3.6 explain and summarize the approach to reach these goals.

3.1. Assembly line B/G/E at BMW

The assembly line B/G/E was in pilot production at the beginning of the thesis in October 2014. With a weekly output of approximately 50 engines, the production will increase up to 495 engines per shift after SOP in April 2015.

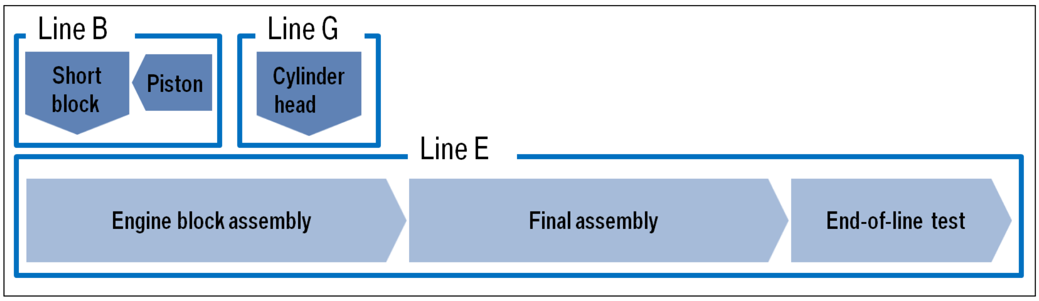


Figure 30.: Areas of the B48 and B58 modular kit engine assembly line (BMW Group, 2012)

The assembly line is clustered in five areas, illustrated in Figure 30. Line B and G are both pre-assembly lines for the main line E and have a high degree of automation. Line B, the so-called *short block assembly*, produces a fully functional and tested engine block with crankcase, crankshaft, pistons, connecting rods and balance shafts as main components. The *cylinder head assembly*, line G, has six manual and 18 automatic workstations. The main components are the intake and outlet camshaft, valves and components for the Variable Valve Timing (VVT) such as an eccentric shaft and actuator. The buffers between short block and cylinder head assembly to the main assembly line are not larger than 50 to 100 units, which represents a production of 1 to 1,5 hours.

The *engine block assembly*, as part of the main assembly line E, starts with the short block from line B and assembles various sensors, components for the oil-circulation system, the cylinder head from line G, parts for the fuel injection system and the heat management system amongst other parts. All components with potential for automated tightening of screwing connections, as well as all process steps requiring a high precision of workpiece carriers are concentrated in the engine block assembly. At the end of this area, the engines are tested for leak tightness.

The complexity of the engine block assembly is very high, due to the large number of workstations. There are 24 manual workstations and 18 automatic workstations assembling components of the B48 and B58 engines. Table 3 gives an overview of the number of manual and automatic workstations in the assembly line B/G/E.

Area	Manual	Automatic
Short block assembly	4	20
Cylinder head assembly	6	18
Engine block assembly	24	18
Final assembly	23	1
End-of-line-test	5	6

Table 3.: Number of workstations in the assembly line B/G/E

The *final assembly* receives the tested engine block and operators assemble components like exhaust turbocharger, intake system, automotive wiring harnesses and various wires and tubes. This area is very flexible in terms of engine position and assembly line balancing, due to the Electric Monorail System (EMS) and only one automatic station. But at the same time, variants increase because of the customization in this stage of the production, which leads to an increase in complexity.

The last area before the engines are transported to an international car assembly factory, is the *end-of-line test*. The engines are set up for a second leak test, filled with engine oil and run through a final function test for example, friction coefficient of the crankshaft, valve lift distribution. When the engine passes the final test, final components are assembled, such as the clutch for cars with a manual gearbox and then proceeds through a camera station for a final check.

The focus of this thesis is narrowed down from the five areas to the cylinder head and engine block assembly. Only selected parts of the final assembly and the end-of-line-test are investigated.

3.1.1. Symbols and denotation

The layouts and flow charts for this thesis will be according to the symbols shown in Figure 31. There are two types of symbols for workstations; the one on the left-hand side is used for general layouts, whereas the other one is used in detailed layouts with description. Turning tables, lifting tables and preliminary stops are part of the assembly line and are important to understanding possibilities in the assembly sequence. Operators are represented as illustrated in the legend for symbols, Figure 31. The material flow is illustrated with arrows and operator movements with bold dotted lines in the direction of the movement.

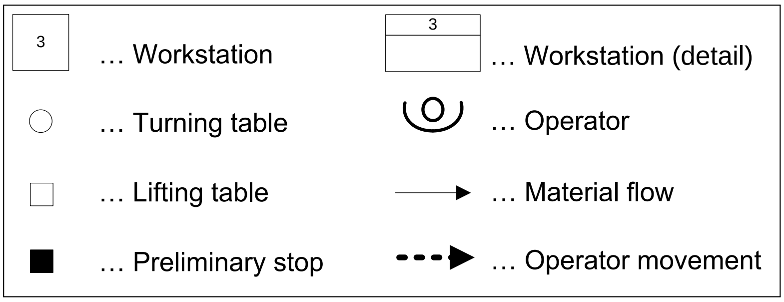


Figure 31.: Legend for symbols (personal design)

The idle time is the difference between takt time and cycle time, which is defined in Section 2.3.1 on page 24. This thesis introduces the term *takt balance*, which can also be negative compared to idle time. This is important as the assembly lines at BMW are mixed model assembly lines and some derivatives can have a negative takt balance, cf. Section 3.1.5.

The diagrams illustrating a line balance of workstations follow the scheme of Figure 32. The green line is indicating the takt time, the predetermined time of the work content, cycle time, is represented by the blue part of the column and the red part of the column is the takt balance. The times shown in the diagrams are in minutes. The number below the column refers to the workstation.

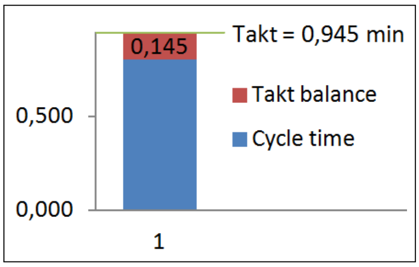


Figure 32.: Diagram for workstations

The workstations of assembly line B/G/E are named as illustrated in Figure 33. The first letter represents the area; the second letter, the line; the third letter, the type of workstation and the last three digits, the number of the workstation. The letter representing the area is derived from the German name of the area. The letter for the line is either B, G or E.

Area	Type
F - Final assembly	A - Automatic
R - Engine block assembly	E - Elevator
S - Short block	M - Manual
T - End-of-line-test	R - Repair
Z - Cylinder head	

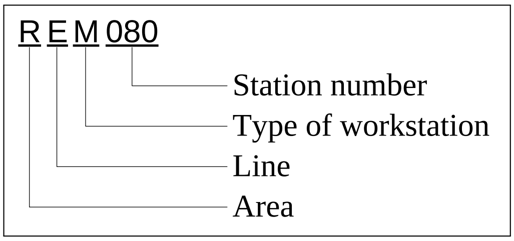


Figure 33.: Legend for denotations

3.1.2. Reference system

The assembly line B/G/E is based on a *reference production system* developed at BMW for the modular kit architecture of three-, four- and six-cylinder petrol and diesel engines. The reference production system represents and an idealized, comprehensive assembly concept for high-cost countries in BMW's engine production network in Munich, Steyr and Hams-Hall. The basic premise of the reference system is the highest possible compliance with the assembly sequence, latest possible customization in the production process and earliest possible error detection.

A precedence graph in the reference system defines the ideal assembly sequence for the main components and parts of the engine. Manual and automatic process steps with consideration of quality and ergonomic requirements are predefined and should be similar among all modular kit assembly lines. Process steps that cannot be performed manually without support, represent fixed-points or anchors in the assembly line. These anchors include steps with special consideration of quality for example, application of sealing material; ergonomic requirements for example, lifting of crankcases; or stationary mounting devices. These fixed-points constrain the flexibility of the workstations within the assembly line because certain tasks have to be performed at this workstation.

Product and process modular kits work hand-in hand and build a stable foundation for the assembly sequence. Product modular kits define common parts in different engine variants with the goal to lower costs of development, economies of scale for sourcing and simplified process planning for the manufacturing and assembly lines. Process or feature modular kits define process relevant features for machining and assembly operations. They represent an agreement between product development and process planning.

The overall goal of the reference production system for the modular kit engines is to reach stable boundary conditions for process partners, standardization of assembly systems and reduction of variants.

3.1.3. Operating mode

The engines flow on workpiece carriers from station to station through the assembly line. Figure 34 illustrates an engine on a workpiece carrier in the engine block assembly, with a so-called “engine set” on the left-hand side, carrying parts for assembly. Additionally, a socket magazine with a release button on top, is displayed in the lower left corner. In the top center of Figure 34 is a handheld angled power screwdriver and a Direct Part Mark (DPM) code reader. The final assembly uses an electric monorail system (EMS) for the transportation of the engines. Figure 35 shows engine sets in the final assembly, which are the black drawers left and right of the engine.

Every workstation is equipped with a release button or pulling line, which the worker can press or pull if all release conditions are met. Release conditions are for example “OK” for correct screwing connections or DPM code scan for mounted parts. The “OK” is signalized on the terminal display at the workstations, which are linked to a Product Data Management (PDM) system. If the system displays a “Not OK (nOK)” signal, the worker can either correct the task or send the engine to a repair workstation, depending on the error.

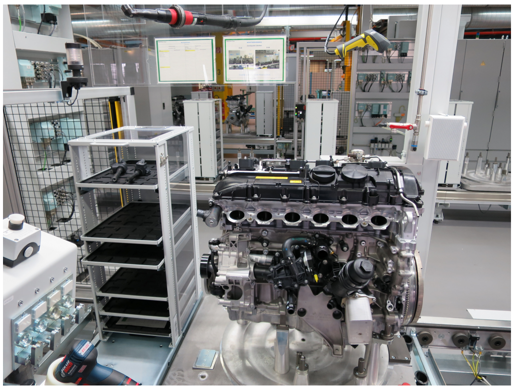


Figure 34.: Workpiece carrier (WPC)

Figure 35.: Electric monorail system (EMS)

Figure 36 illustrates the operating mode of the assembly line, with operator triggered release for the workpiece carriers. Every workstation has a preliminary stop to receive a new engine when pressing the release button.

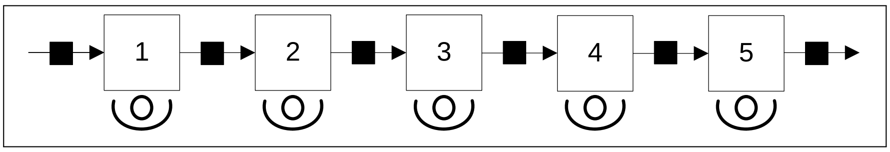


Figure 36.: Operating mode - operator triggered release

3.1.4. Takt time

The ideal takt time for automatic and manual workstations is defined in the reference production system. This takes into consideration losses caused by defects, efficiency and downtime.

The standard shift length at BMW Steyr is 8,3 hours of paid attendance time, which equals to 498 minutes. Taking into consideration 30 minutes of paid attendance time for a paid break and factual allowance time for preparation, short interruptions, group meetings and cleaning; the effective operating time is reduced to 468 minutes, which is the basis for the takt time calculation. Table 4 shows the calculation of the effective operating time according to Chapter 2.2.5, page 17.

528 min	Total attendance time
-30 min	Lunch (not paid)
498 min	Paid attendance time
-15 min	Paid collective break
-15 min	Factual allowance time
468 min	Effective operating time

Table 4.: Standard shift length at BMW Steyr

The calculation of the takt time for the manual workstations of line B/G/E, according to the reference production system, follows Equation 2.1. With an effective operating time per shift of 468 minutes, and a production output of 495 engines, the takt time of every workstation in the assembly line is 0,945 minutes or 56,7 seconds, shown in Equation 3.1.

$$\text{Takt time} = \frac{\text{Effective operating time}}{\text{Production output}} = \frac{468}{495}\frac{\text{min}}{\text{engines}} = 0,945\frac{\text{min}}{\text{engine}} \tag{3.1}$$

3.1.5. Product mix

The two basic engines assembled in line B/G/E are the B48 and B58 engines. The six-cylinder engines usually require more time to assemble due to the additional cylinders, the B48 engines however, have additional parts. The difference between work requirements of the engines at some workstations, leads to a line balance with mixed times. The product mix for the thesis is defined as 60% B48 and 40% B58, constant over the period of consideration.

Influence on line balancing. Figure 37 shows the common practice of using mixed times for balancing workstations. Where one or more derivatives have a negative takt balance but the weighted average cycle time is below or at the takt time. The average is calculated according to the product mix. A premise for this is a leveled production (Section 2.2.7) without batches of engines with higher processing time and respectively higher cycle times, which otherwise would lead to a bottleneck in the assembly line.

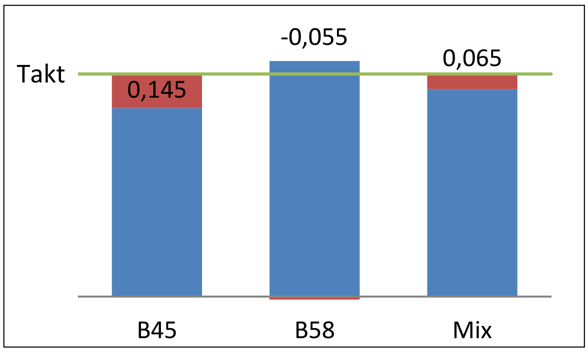


Figure 37.: Line balance with different cycle times for B48 and B58

A significant change of the product mix requires a new line balance in order utilize the workstations at or below takt time. The goal is to create a stable line balance, as the variants depend on the customer demand and are not influenced by the assembly department.

3.1.6. Organizational structure of assembly line B/G/E

The organizational structure of the blue collar workers, also referred to as primary personnel, can be categorized in four types.

- **Foreman.** The foreman or lead assistant is responsible for manual and automatic workstations in a designated area and coordinates operators up to a group size of ten. Foremen also cover the personal allowance time of operators as a jumper and support them during assembly. As a requirement, they need to know all tasks within the area. The foreman supports the redistribution of work contents, line balancing, to reach the targets, as they have intricate knowledge in assembling the engines.

- **Line runner.** The line runner or the machine operator resolves errors of highly automated workstations and conducts minor maintenance and repair works. Small logistic contents like refilling bolts, nuts and parts for automatic stations is a responsibility of the line runner.

- **Repair worker.** The main task of the repair or rework worker is the re-certification of engines and supervision of test stands for example, the leak test.

- **Operator.** The operator or production worker assembles engines at manual workstations and is bound to the takt time. They have proficient knowledge and skills for approximately five workstations and they conduct quality checks and resolve simple errors for example, nOK from electric power screwdrivers.

The total number of primary personnel is important for the calculation of the total processing time per engine at BMW.

3.1.7. Processing time

Figure 38 illustrates a detailed breakdown of the engine processing time at BMW, according to the structure of Figure in Section 2.4.5. The basic time is the sum of the activity time and the takt balance. The activity time is the total the total of the cycle times of the workstations. It is further divided into value-adding, which represents the main activity, and non-value-adding activity, representing ancillary activities. At BMW the non-value-adding activities are further categorized into activities for process support (P), logistic (L) and quality (Q).

The factual allowance time at BMW is 15 minutes. The personal allowance time of 10 minutes is covered by the jumper, which is the responsibility of the foremen at plant Steyr. The time for process support t_{PS} represents the foremen and line runner and t_r represents repair workers. The downtime balance t_{DB} is a planned compensation for small organizational and technical disturbances.

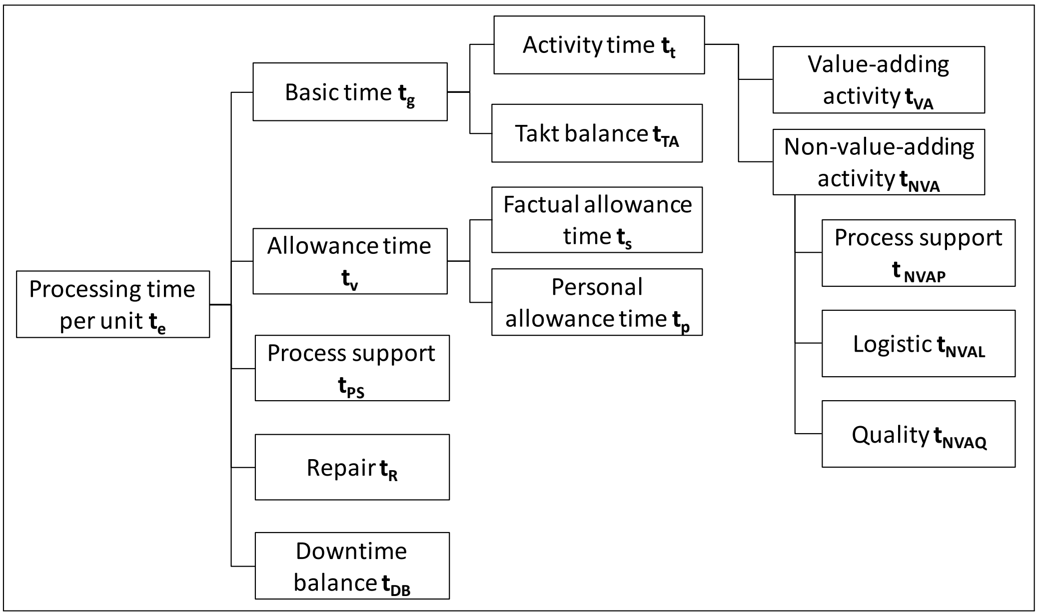


Figure 38.: Structure of the processing time related to the engine

This structure is used to report the processing time per engine. Figure 39 shows the same processing time per engine in a block diagram. The activity time and the takt balance represent the number of operators working in the assembly line bound to takt time. The basic time, activity time and takt balance, is directly derived from the actual line balance and is therefore referred to as total cycle time.

Foreman and line runner, the process support, and repair worker are referred to as “structure” personnel. The idle time includes downtime balance, as well as 15 minutes for the collective break and 15 minutes of factual allowance time of the entire labor quantity, which includes operators and structure personnel. The allowance time is separated and included in the idle time to guarantee comparability between production plants with different labor regulations.

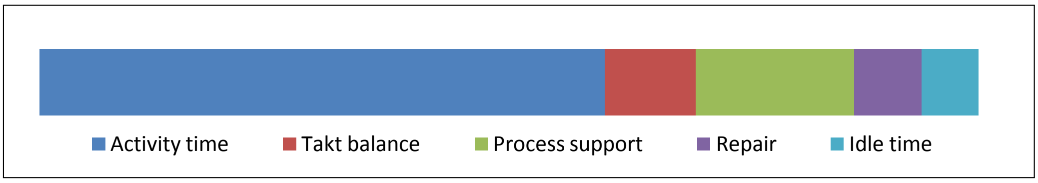


Figure 39.: Processing time per engine

The relation between processing time per engine and the amount of workers, labor quantity, is defined in Equation 3.2. The processing time equals labor quantity multiplied by attendance time, divided by production output. Either the paid attendance time or the effective operating time is used in the calculation, depending on the required result, cf. Table 4, page 44

$$\text{Processing time} = \text{Labor quantity} * \frac{\text{Attendance time}}{\text{Production output}} \tag{3.2}$$

Influencing factors

The direct relation between processing time and labor quantity, defined in Equation 3.2, makes it possible to derive the influencing factors for improving the processing time and therefore the productivity. According to Section 2.4.1, productivity can be improved by either producing more units with the same amount of workers, or producing the same amount with a lower amount of workers.

- **Labor quantity.** The amount of workers assembling engines are defined by the line balance. The labor quantity directly influences the processing time. Workstations can be optimized by reducing non-value-added tasks and redistributing work content, hence productivity is improved.

- **Shift length.** The processing time is always set at the standard shift length of 8,3 hours. Without any changes of the workstations in the assembly line, the production output increases proportionally with an increase of the effective operating time. Thus productivity cannot be improved by varying the shift length.

- **Production output.** Increasing the production output in a fixed period of time will lead to a productivity increase and a decrease of the processing time. A change in the production output influences the takt time inversely proportional, cf. Equation 3.1.

- **Product mix.** The product mix influences the total processing time with the amount of work required for the engine derivatives, cf. Figure 37.

Direct and indirect productivity increases

A *direct productivity increase* is a reduction in processing time can be reached by either reducing the amount of blue collar workers, labor quantity, or increase the number of engines produced in a standard shift. A reduction of operators decreases the basic time t_g, a reduction of foremen or line runners decreases t_{PS} and a reduction of repair workers decreases t_R, cf. Figure 38.

Increasing the production output reduces the takt time and the takt balance, not the activity time. Also the share of structure personnel per engine is reduced by increasing the output. This is only possible if all areas of the assembly line B/G/E increase the production output and all workstations have a sufficient takt balance.

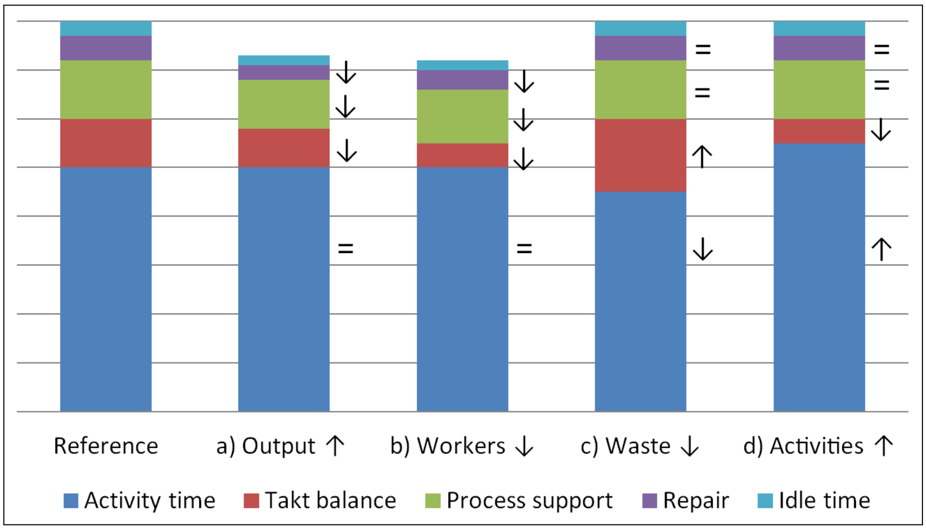


Figure 40.: Different types of productivity increases

Indirect productivity increases represent optimization without a change in labor quantity or production output and therefore, no change in the total processing time of the engine. One way to reach indirect increases in productivity is by reducing non-value-added activities or waste. The amount of time representing eliminated waste is then takt balance, cf. Section 3.2.3, page 63ff.

The same effect can be attained by adding or removing work content and therefore decreasing or increasing takt balance. This transfer of work content is between process partners such as, from logistics to assembly, or vice versa. The work content also changes depending on the product mix.

Figure 40 summarizes the effects of direct and indirect productivity increases. The column on the left-hand side represents a reference processing time and the arrows an increase or decrease. Column a and b illustrate a direct productivity increase, whereas column c and d show indirect increases.

3.1.8. Definition of initial situation and targets

The initial processing time per engine for a product mix of 60% B48 and 40% B58 engines was 76,044 minutes, which equals to a total labor quantity of 76. Table 5 lists the labor quantity for the investigated areas, including the structure personnel, at the defined start of December 2014. It is important to define the initial labor quantity, in order to calculate the productivity increase.

Area	**Labor quantity**
Structure personnel	18
Cylinder head assembly	6
Engine block assembly	24
Final assembly	23
End-of-line-test	5
Sum	**76**

Table 5.: Labor quantity for assembly line G/E in December 2014

The target of the thesis, defined in Section 1.3, is to reach an annual productivity increase of 6%. The measures to realize the goals are defined in a productivity roadmap for 2016 and 2017. Table 6 defines the target processing time and the labor quantity for an annual productivity increase of 6% for the considered period in December of every year.

Target	**12/2015**	**12/2016**	**12/2017**
Processing time [min]	71,604	67,307	63,269
Labor quantity	71	67	63

Table 6.: Target labor quantity for assembly line G/E

3.1.9. Productivity roadmap

The productivity roadmap is a central tool in BMW's engine production network. Basis for the processing time per engine is the labor attendance time and the actual units produced in a defined period of time and in a defined organizational unit, cf. Section 3.1.7.

Processing time/engine at ZM-4. Roadmap to reach productivity increases of 1% per month.

Pertol engine assembly B48B/B58 Line G/E (ZM-48)

2015: Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Measure/concept	Productivity: - Labor quantity (in #/day)	Productivity: + Output per shift (in units)	Productivity increase [Total] in %	Productivity increase [Imputed value] in %
A Use of VPS-Methods	**-3,0 #**		**3,95%**	**3,73%**
Utilization of run-in times	-2 #		2,63%	2,63%
Reduction of one operator	-1 #		1,32%	1,10%
B Automation	**-0,949 #**		**1,25%**	**1,05%**
Automate DPM code scan	-0,054 #		0,07%	0,06%
Full automation of semi-automatic machine	-0,896 #		1,18%	0,98%
C Product improvement	**-0,3 #**		**0,36%**	**0,18%**
Screws for injector rail: elimination of initial screwing	-0,177 #		0,23%	0,14%
No lubrication of O-rings in final assembly	-0,099 #		0,13%	0,04%
D Line balancing (change of takt time)	**-0,4**		**2,55%**	**2,07%**
Increase of production output from 495 to 505	#	10 #	2,02%	1,85%
Increase of B58 engines	-0,4 #		0,53%	0,22%
E Opposing effects	**1,2 #**		**-1,58%**	**-0,99%**
Increase of B48 engines	0,2 #		-0,26%	-0,11%
Additional quality check	1 #		-1,32%	-0,88%
Sum	**-3,4 #**		**6,53%**	**6,04%**

Legend:
... Green milestone: measure effective from
... Yellow milestone: measure presumably effective fron
... Red milestone: realization questionable
... Measure with limited effec

Figure 41.: Productivity roadmap

Figure 41 outlines the scheme with an example of a roadmap used at BMW. The roadmap is structured in five categories:

- **A) Use of VPS-methods.** Measures that are defined in the roadmap, that relate to using the methods provided in the Value-added Production System of BMW, are listed in this category. VPS methods used in this thesis are described in Section 3.2.
- **B) Automation.** Every automation that leads to a decrease in processing time and therefore to an increase in productivity, is listed in category B.
- **C) Product improvement.** Improvements regarding product or parts of the product, are listed as product improvement. For example parts that do not require further lubrication or screws that do not need initial tightening.
- **D) Re-balancing.** Every line balance linked to a change of the takt time, and changes in the product mix that make assembly workstations more productive are listed in this category. The takt time is calculated with standard shift and production output (cf. Section 3.1.4), therefore the takt time changes with a change of the production output. The takt time for this thesis is set to 0,945 minutes as defined in Equation 3.1, and the product mix is fixed as well, therefore this category will not be used.
- **E) Opposing effects.** Quality checks, fluctuations with negative influence on product mix or additional activities without a budget increase, is listed in category E.

Direct productivity increases, a reduction of labor quantity or increased production output, which reduce the processing time are directly entered in the roadmap. Indirect productivity increases are calculated to labor quantity by rearranging Equation 3.2. An example calculation for a productivity increase with processing time is illustrated in Equation 3.3.

$$\text{Labor quantity} = \text{Processing time} * \frac{\text{Production output}}{\text{Attendance time}} = 0,350 \text{ min} * \frac{495 \text{ units}}{498 \text{ min}} = 0,348 \ \# \quad (3.3)$$

The total percentage value is calculated to either the labor quantity or the production output. As not all measures are effective from the beginning of the year, the imputed value represents the proportional contribution of the productivity increase of the measure. The sum of the imputed values of the single categories should amount to 6%, as defined in the targets.

3.2. Tools and Methods

This section describes the tools and methods used in the practical part of this thesis. The BMW standard data is the common industrial engineering tool for calculating predetermined times in the BMW production factories. The methods for process analyses are described in the Value-added Production System of BMW and are used to identify potentials in the assembly line. The principles for distributing work content are important for creating a stable line balance.

3.2.1. BMW standard data

BMW uses MTM the worldwide leading method for analyzing and assessing of manual operations, cf. Section 2.4.3. Motion sequences for operations can be determined and optimized during the planning phase. BMW developed standard data based on MTM to create an internationally standardized analyzing system, which is used in all locations of the BMW Group. The BMW standard data are specified for operations in the automotive industry and is the foundation for industrial engineering and operations in the company. The goal of the standard data is to simplify the analysis of work tasks, create reproducibility and sufficient accuracy, as well as enable the computer-based application.

Get and Place				Code	Distance range		
					1	2	3
≤ 1 kg ≤ 2.2 lb	easy	1 part or simult.	aprox.	S-AAE	20	35	50
			loose	S-ABE	30	45	60
			tight	S-ACE	40	55	70
		2 parts.	aprox.	S-AAZ	20	35	50
			loose	S-ABZ	50	65	80
			tight	S-ACZ	70	85	100
	difficult	1 part	aprox.	S-ADE	20	45	60
			loose	S-AEE	30	55	70
			tight	S-AFE	40	65	80
		2 parts	aprox.	S-ADZ	40	65	80
			loose	S-AEZ	60	85	100
			tight	S-AFZ	80	105	120
		simult.	loose	S-AES	50	75	90
			tight	S-AFS	60	85	100
	handful		aprox.	S-AGH	40	65	80
	handful, throw remainder back		aprox.	S-AGHR	50	85	105

Figure 42.: BMW standard data - example [units in TMU]

The most important categories of the BMW standard data for assembling engines are *Get and place*, *Place* and *Working with screws and bolts*, illustrated in Appendix A.1. Figure 42 shows a part of the category *Get and place*, with the self-explanatory subcategories of weight, complexity of getting, placing the part and the number of parts. The distance range describes the reach zones for the parts being used, cf. Figure 27 in Section 2.4.2.

Distance range 1 is up to 20cm, range 2 up to 50cm and range 3 up to 80cm. Picking up and placing one part below one kg in distance range 3 would be 50 TMU, code S-AAE3. According to Table 2, 1 second equals 27,8 TMU (Time Measurement Unit); The production plant in Steyr has a *performance rating* of 120%, which results in 1,5 seconds, see Equation 3.4.

$$\text{S-AAE3:}\ \ 50TMU/27,8/120\% = 1,5s \tag{3.4}$$

Figure 43 illustrates tasks and the influence of different reach areas for operators on the basis of BMW standard data. Picking up the same part as in the example of Equation 3.4 in distance area 2 leads to a predetermined time of 1,05 seconds and a decrease of 0,45 seconds. Over 80cm, the analysis according to BMW standard data, is walking one meter twice (Code: S-KAM with 25 TMU) plus distance range 1. The calculation for the example is shown in Equation 3.5.

$$\text{Pick up and place >80cm:}\ \ (2*25+20)TMU/27,8/120\% = 2,1s \tag{3.5}$$

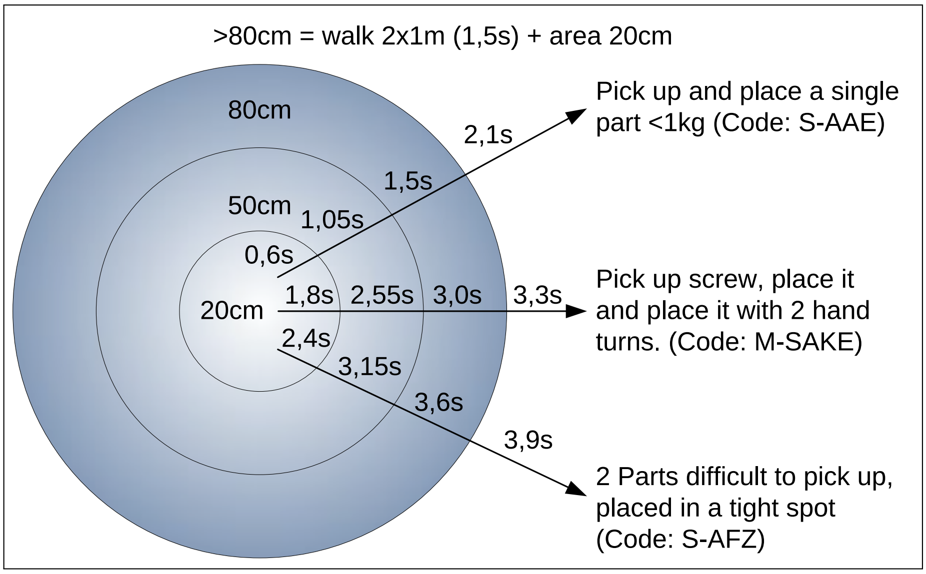


Figure 43.: Reach areas for operators

The code from the BMW standard data sheets is used for computer-based application and defines value-adding and non-value-adding activities (P, L and Q), cf. Figure 38.

3.2.2. Process analysis

To improve process efficiency and stability, it is necessary to recognize and identify potentials and then develop them in a structured fashion. This section describes the types of analysis used in this thesis, which are an integral part in the Value-added Production System of BMW. The identified potentials of assembly line B/G/E found during the process analysis are structured and detailed at the end of this section.

EKUV analysis

EKUV is the abbreviation for the German version of eliminate, combine, redistribute and simplify. It is used to generate ideas for workplace optimization and it's goal it to reach the maximum output nwith minimum input. Four central questions are used in this method:

- Which activities are unnecessary and can be left out?
- Which activities can be performed simultaneously?
- Which activities can be reasonably moved?
- Which activities can be improved or made easier?

Eliminate. Check if single or multiple activities can be left out to only perform what is really necessary. The main focus in this step is on identifying and eliminating waste, non-value-added activities, over-processing, idle time, defects and errors. For example, elimination of walking distances through optimized material supply.

Combine. Check if activities can be performed at the same time to shorten the processing time. It is important to consider informational dependencies between activities and process steps. An example, for combination is the possibility for two-handed grasping of part and tool, through optimizing the layout.

Redistribute. Check if redistribution can improve utilization of resources, shorten lead times or ease the distinction between value-added activities and waste. For example, performing activities during machining times which can be achieved through redistribution.

Simplify. Check how activities can be designed to minimize effort for controlling, checking, positioning and handling activities. The definition shall not be as precise as possible, but as precise as necessary. For example, using a mounting gauge for easier assembly of parts.

Chalk circle

The "chalk circle" is a systematic and structured method to analyze processes. Value creation and waste are separately observed and causes of waste are identified by visual snapshot analysis. It is an integral part of the shopfloor management and is mainly used for workplace optimization, scanning of potentials for improvement and process step optimization. The chalk circle method promotes understanding of processes and develops skills in recognizing and evaluating value-added activities and waste. By providing an external view, this tool should help to examine hidden problems of familiar processes. For processes with a takt time of around 60 seconds, it is recommended to schedule at least one hour on-site to get a rough overview.

It is necessary to establish appropriate, process-specific key indicators in advance, by focusing on the eight types of waste, cf. Section 2.2.1. These indicators can then be quantified in the observation. Indicators for assembly processes, according to the BMW VPS, can be:

- Takt times
- Cycle times
- Waiting times
- Processing times
- Inventory coverage (in hours)
- Area and space (m^2, m^3)
- Error and rework (ppm)
- Ergonomic movements
- Walking distances (m)
- Packing density (parts/container)
- Multiple part handling
- Material handling situation

Scope definition is necessary to focus on the most important aspects. It is determined by the desired outcome; observing a single process for example, assembling operation; an entire workstation (multiple operations); a complete process area for example, engine block assembly - considering routes, areas, ergonomics, process sequence, cycle times, inventories, etc.; or even a process interface for example, between logistics and assembly.

Before literally drawing a circle with a piece of chalk, approximately 1m in diameter, to define the place of observation, it is important to inform the operators and involve them. The workers are able to give vital input in selecting the point of observation, as well as knowledge and experience about the process to be observed. The point of observation should provide unrestricted view of the area without disturbing the operation.

The snapshot observation during the chalk circle should be divided into two phases: *overall view* and *detailed examination*. The goal in the first phase is to get a holistic overview about the process. It might have to be observed several times, depending on complexity and scope. In general, more than 10 cycles or at least 30 minutes are suggested. After gaining an overview, the process is examined in detail by intensively observing the smallest steps. This phase can take several hours depending on scope and complexity. The focus of the second phase should be on the current situation of the process for example, assembly sequence, layout, routes as they actually are, and on every possibility for improvement, no matter how small.

This method was mainly used during performance tests of assembly line B/G/E. The weekly production output of approximately 50 units did not provide sufficient stability and serial-like production. The basic principles were applied during all process analyses.

Spaghetti diagram

A well know and frequently used tool for waste analysis and a standard tool in the Value-added Production System at BMW, is the "Spaghetti diagram". It is also known as a route or movement diagram. This diagram is often used in mass production to visualize the product's paths down the value stream and is so-called, as the route often looks like a plate of spaghetti (Womack & Jones, 2003, p. 352).

As this thesis focuses on workstations, the spaghetti diagram is used to illustrate the walking paths of operators in the assembly line. The first step is to create a map in plan view of the workstation. It is important to indicate the structure of the workstation, objects in the facility and the material handling situation. With this map it is possible to draw movements in the order of execution and track them by numbering the lines.

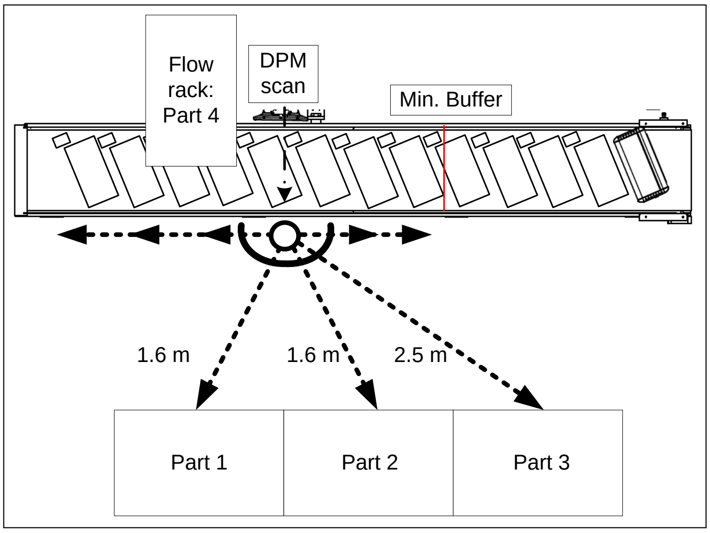


Figure 44.: Spaghetti diagram

Figure 44 illustrates an example of a spaghetti diagram. The movements of the operator are indicated by the dotted lines, including the distance. This is important to calculate target times according the BMW standard data, where 1m equals 25 TMU. The distances are weighted according to the product mix and therefore the consumption of the parts.

Identified potentials

This section describes the categories of the main identified potentials to reduce the processing time and explains examples for line B/G/E.

Update existing line balance. The line balance is based on an iterative process, cf. Section 3.2.3 on page 63. To to get an accurate line balance, it is important to re-analyze the operations. The operations consider specific information about distance ranges, walking distances and material handling situations, which influence the target times and therefore the basis for the line balance.

The initial line balance of assembly line B/G/E was to a high degree based on a planned version of the operations. Hence the line balance contains superfluous operations, which are not according to serial operation status. An intense analysis of the operations in the engine block assembly shows a potential for a decrease in target time of 0,766 minutes.

Some operations can be combined to reduce the target time. For example, selected screwing connections which require the same screwdriver and tightening torque. Workstation REM 100 tightens 4 bolts; the analysis showed three operations with two extra operations picking up a power screwdriver for the same bolt (Code: M-SFBE3 = 85 TMU), instead of moving the screwdriver to an additional position (Code: M-SFBZ1 = 30 TMU). The combination of the operations in this example reduces the target time by 0,055 min.

These potentials highlight the need for an update of the operations, by assessing distance ranges, material handling situations, as well as the actual process times of screwing connections.

Update process times of power screwdrivers. Unfortunately it is not possible to gather process times of the final screwing from the PDM system, therefore the specialists for IE need to record the actual process times. The planned process times according to the planned version are between 1,5 and 3 seconds. Table 7 shows an overview of the results updating the process times in the engine block assembly and the final assembly. The potential in the cylinder head assembly is by far smaller, due to the small number of screwing connections and amounts to 0,050 minutes for workstation ZGM 190 and 0,033 min for ZGM 210. The total reduction of process time in these three areas add up to 1,153 minutes.

Optimize process times of power screwdrivers. During the determination of the actual process times, further potentials were identified. The initial screwing process, placing the screw in the thread and screwing it in with a cordless screwdriver has a process time of about one second, because of the the high number of revolutions per minute. The process time for the final tightening

	Engine block assembly	Final assembly
Number of screwing connections	38	35
Planned process time (average)	2.6s	2.9s
Actual process time (average)	2.3s	1.6s
Potential (total)	**0.290 min**	**0.780 min**

Table 7.: Potential in process times of screwing connections

process can be significantly decreased by screwing the screws in as far as possible, until head contact. For example, the process time of a fluid pipe was reduced from 3s planned process time to 0,5s actual process time.

Some parts require a loose initial screwing with allowance for clearance. A defined initial screwing can be reached with a special socket developed at BMW. This socket is attached to the bit at the screwdriver and ensures a defined screwing position. In this way it is possible to optimize the overall process time. Figure 45 illustrates an isometric view of a special socket.

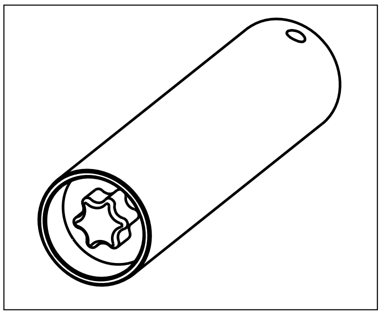


Figure 45.: Special socket for screwdrivers

The next step can be optimizing the tightening program for the power screwdrivers, by increasing the rpm for the screwing process. Table 8 lists parts with potential for further optimization, by either initial screwing to head contact or optimizing the screwing program.

Workstation	Part	Quantity	Time per screwing
REM 100	bolts in the crank case	4	3s
REM 200	oil suction pipe	2	3s
REM 265	knock sensor	2	2s
FEM A31	exhaust turbocharger pipes	3 or 5	3s
FEM 160	heat protection metal sheet	4	2s

Table 8.: Parts with potential for further optimization

Utilize process times. Process times where operators are not bound to the process, are waiting times and can be identified as obvious waste. Naveen & Dalgobind (2013, p. 5) suggest to reduce this waiting time by the parallelization of tasks, cf. Section 3.2.3.

For example, workstation ZGM 171 and ZGM 231 each have process times for lubrication of 0,096 minutes. This time can be utilized, if appropriate work content can be moved to these workstations. In case of workstation 171, one of the portable mounting devices could be placed onto the workpiece carrier with a time of 0,070 min for the operation, and therefore eliminate waiting time by parallelization.

Utilize WPC or EMS run-in times. The process related waiting time caused by workpiece carriers in the engine block assembly and the electric monorail system in the final assembly, is enormous. Table 9 outlines the run-in times in the areas. The total run-in time of the workpiece carriers over 23 workstations in the engine assembly sum up to 3,841 minutes, which is equivalent to 4,1 workstations or takt times. Due to occupational safety regulations, the EMS has even longer run-in times compared to the Workpiece carrier (WPC). The total time amount is 4,161 minutes, an equivalent of 4,3 takt times.

	W/S	Run-in time	Total time	Equivalent
WPC	23	0,167 min	3,841 min	4,1 W/S
EMS	20	0,219 min	4,161 min	4,3 W/S

Table 9.: Run-in times

By utilizing between 0,080 and 0,100 minutes, about 50% of the run-in time, it would be possible to reduce the waiting time by around two minutes. The goal is to perform as many operations during the run-in time and eliminate all non-value-adding time for example, picking up parts, tools or walking.

Table 10 lists examples for operations that can be performed during run-in times. Pulling out engine set drawers is a possibility, as it is always oriented upstream in the engine block assembly. Picking up a part, screws and a screwdriver, including placing one screw into the socket or bit and getting in position for assembly, can be up to 0,100 minutes. Walking to pick up parts during the run-in time can be performed for example, at the workstations REM 238 (oil pan pre-assembly), REM 287 (flywheel pre-assembly), REM 390 (cylinder head cover), as well as the exhaust turbocharger pre-assembly (FEM A3x, FEM 090).

The proportional part per takt time of the release orders is minor, but amounts to about 0,082 min in the engine block assembly and to 0,145 min in the final assembly. The release orders at the terminals to trigger replenishment of the parts should be automatically generated, by either using a counter or an electronic kanban system.

Operation	Potential
Pull out engine set drawer	0,050 min
Pick up screws (handful, throw back remainder)	0,052 min
Pick up part, screws and screwdriver	0,050 - 0,100 min
Walk to pick up parts, or switch workstations	up to 100% of run-in time
Material handling; handling of empty bins	up to 100% of run-in time
Release order for replenishment of parts at terminals	minor

Table 10.: Operations during run-in times

The use of waiting times during WPC and EMS run-in times should be considered to optimize line balancing. It could also be advantageous for selected parts to be provided at the workstation and not in the engine set. This is in order to to perform operations before the WPC stopped at the workstation. It is important to consider all variants when choosing operations during run-in times.

Avoid tool changes for power screwdrivers. Manual workstations in assembly line B/G/E are equipped with up to one pistol grip and one angular power screwdriver, as well as a socket magazine with different bits and wrench sockets linked to the PDM system. On one hand, these socket magazines increase flexibility, but in contrast increase potential sources of unnecessary, non-value-adding activities such as tool changes.

The predetermined time for a tool change according to BMW standard data is 0,063 minutes. To avoid tool changes, it is necessary to distribute the final screwing operations, with a maximum of two, among the workstations.

Avoid workpiece carrier turns. Every manual workstation in the engine block assembly has the possibility to manually turn the WPC, which again increases flexibility in line balancing regarding the position of the engine. But WPC turns are non-value-added activities and mean additional waste which should be eliminated. The time per 90° WPC turn is 0,051 min and per 180° turn is 0,063 min.

As the engines are transported on EMS in the final assembly, it is not possible to turn the engines. But the equivalent to the WPC turns are walking distances and related times around the EMS. The time for walking three meters back and forth to the other side of the EMS is 0,075 minutes.

Combining operations on the same position of the engine in a workstation, can therefore eliminate unnecessary turns and increase productivity.

Optimize workstations. The optimization of the workstations strongly correlates with the influence distance ranges and walking distances, according to BMW standard data, cf. Section 3.2.1. The closer material and tools are to the operator, the lower the predetermined time for operations. The influence of reach areas for selected examples are illustrated in Figure 43. A reduction of walking one meter back and forth to distance range 3 (50 to 80cm) is up to 0,010 min and from range 3 to range 2 (20 to 50 cm) up to 0,008 min.

The amount of material handling operations, including empty bins and containers, should be minimized, as acyclic operations should be avoided for assembly workers. The optimum for assembly workstations are bins in a flow rack close to the assembly position.

The optimization of the workstations is strongly oriented on Section 2.4.2. The parts presentation as described according to the reach zones correlates with the influence of the distance ranges. The principles of rational workplace layout as elaborated by Pheasant (2003, p. 46) are also useful in optimizing the manual workstations in the assembly line.

Optimize interface between assembly and logistics. The reference system defines a clear interface between assembly and logistics operations, which is important for process planning and targets the separation and individual optimization of the processes. The ideal situation for assembly workers is a minimum amount material handling and acyclic operations. Furthermore an employer/works council agreement in Steyr defines, that logistics workers are not allowed to assemble parts of any kind.

This leads to certain non-productive interfaces from a holistic point of view. Some workstations are not fully utilized on both sides of the interface. By transferring operations, such as material handling beyond empty bin manipulation to assembly workers, workstations can be more productive and the amount of logistics workers may be reduced. This is in some way the opposite direction of optimizing workstations from an assembly point of view, cf. Paragraph Optimize workstations.

The intake system pre-assembly (FEM S20) in the final assembly area is one example. Further details for this example are described in Section 3.5.

Simple automation. Simple automation in this case means, use of equipment or tools which do not require full automatic stations. This can either be Low-cost intelligent automation (LCIA) solutions, handheld multi power screwdrivers with multiple spindles or fixed-mount DPM code readers.

An example for reducing the processing time is the use of a handheld multi power screwdriver in the cylinder head assembly. An angular power screwdriver with one spindle is currently used at

ZGM 190. A multi power screwdriver would lead to a reduction of 0,117 minutes. More examples for simple automation are described in Sections 3.2.5 to 3.2.7.

Automation. Use of full automation is a common practice to reduce the processing time and related labor costs. The possible automation examples used in this thesis are based on the reference system and existing automatic stations of other assembly lines at BMW. Automation is most of the time very expensive and strongly decreases flexibility in line balancing in terms of changes in production output and related takt time changes. The focus of the thesis is not on automation and will not go into further detail.

3.2.3. Assembly line balancing

Section 3.2.3 describes assembly line balancing as the distribution of the total workload of a product among the workstations, with the main object of increasing productivity by reducing waste such as operator waiting time.

The goal of line balancing at BMW is to achieve principles of “takt” and “one-piece flow”, according to the Value-added Production System (VPS). Further targets are avoiding irregularities, increasing ergonomics and creating a stable work environment and increase of process quality, which forms the basis for continuous improvement. It is therefore necessary to distribute all assembly operations among the assembly line. By assessing the situation it is possible to find imbalances, such as overload or under-utilization.

Iteration process of line balancing

The process of line balancing starts with defining operations, which according to Scholl (1999, p. 4f) are tasks of the total work content that cannot be split into smaller pieces without adding unnecessary additional work, cf. Section 2.3.1. The target times are calculated with Computer-aided process planning (CAPP) software, based on the BMW standard data. Table 11 shows an example of an operation. The operator first picks up screws, throws back remainders, then picks up the screwdriver, places a screw in the tool and places it; then sets down the screwdriver after a process time of 27,8 TMU (1s). In this case the screwdriver and the screws are placed in distance range 3.

No.	Code	Target time	Description
001	S-AGHR3	105 TMU	Pick up screws
002	M-SFBE3	85 TMU	Pick screwdriver, place in position, set down
003	S-PBE1	20 TMU	Place screw in screwdriver
004	S-PTG	27,8 TMU	process time

Table 11.: Example of an operation

The total work content is divided into such operations with the calculated target times. Under consideration of the assembly sequence and boundary conditions such as stationary mounting devices or automatic stations, the distribution of work content (line balancing) can take place. It is important to understand the assembly sequence and boundary conditions for the parts being assembled. Section 2.3.1 describes the application of a precedence diagram with nods, visualizing the required order. The use of such diagrams was spared in this thesis, because the application was evaluated as not practical by experts at BMW. The assembly sequence will be explained in the according sections, evaluating the possible assembly positions depending on position of the WPC and the ergonomic situation.

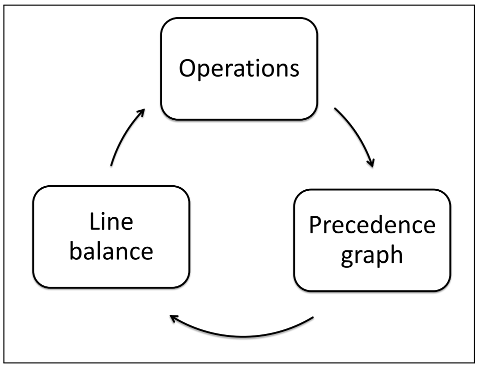


Figure 46.: Iteration process of line balancing

The initial operations are based on a planned version and have to be updated after implementing the line balance. The operations now consider actual reach areas and walking distances, because they influence the target time and therefore the line balance. Every adaption of a workstation requires a re-assessment of the operations in order to get the accurate target times. Figure 46 illustrates the iterative process of calculating operations and line balancing. For this reason, the prerequisites for assembly line balancing are an understanding of the assembly process, including parts, automatic stations, assembly sequence as well as the principles of line balancing.

Principles of line balancing

Balancing assembly lines by distributing the work content follows certain principles described in this section. Starting with an initial line balance the process follows the same optimization process as described in Section 3.2.3. The initial situation is first assessed and distinguished between value-added and non-value-added activities, also on level of single operations. Then potentials for improvement by reducing non-value-added tasks, as well as predetermined times for value-added tasks, and redistributing of work contents are defined. The goal is to fill the takt balance of the workstations with (value-added) operations to increase productivity.

Rother et al. (2006) describe the *lean oriented* line balancing, where workstations should be fully utilized and waste in form of waiting time should be concentrated to one workstation. This makes the under-utilization more visible and easier to identify further potential in other workstations, cf. Paragraph [p. 53f]Two types of line balancing in Section 2.3.3, page 27. The suggested 85% rule by Ortiz (2006, p. 49), where assembly lines are utilized 85% of the takt time, is not applied at BMW, cf. Section 3.2.3, page 63.

The influence of the product mix on line balancing described in Section 3.1.5 can be very significant. The cycle time spread between the single derivatives and the use of mixed times can make the line balance unstable towards changes in the product mix. A principle or objective in line balancing is to create stable work cycles for all workstations and avoid over-utilization. This simply means one or more derivatives need more time to assemble and the cycle time is longer than the takt, which leads to a negative takt balance. Törenli (2009, p. 20) mentions an increase of losses and therefore a decrease in productivity with increasing variants produced, especially for workstations with a fixed number of operators, cf. Section 3.2.3.

Creating these *stable work cycles* can be reached by separation of tasks for all variants and extra operation. This can either be realized by creating extra workstations in the line or creating subassemblies. Both of these options are hard to realize for a spread between four- and six-cylinder engines and at the same time run the assembly line productively. Additionally, this would require many extra workstations which increases the length. Nevertheless, the aim it to reach a stable line balance by targeting stable work cycles with a small spread in cycle times among variants.

The WPC can only be released when the final tightening operation with power screwdrivers is performed correctly and the PDM systems signals “OK”. To increase in-process reliability of the assembly operations it is beneficial to perform placement of screws and final tightening tasks at the same workstation.

Further principles can be derived from the identified potentials in Section 3.2.2: Only place two final tightening operations at one workstation in order to *avoid tool changes*. As a standard manual workstation is equipped with two power screwdrivers and a socket magazine with the necessary bits and sockets. The flexibility of *turning workpiece carriers* and walking around EMS, immensely increases flexibility, but as well inherits a potential for waste. Due to this reason operations requiring the same engine position should be combined in one workstation to avoid additional time caused by movement or motion. Operations such as picking up parts, screws and screwdrivers should be considered in the process of line balancing to be able to *utilize run-in times* of WPC or EMS.

BMW chaku-chaku

It is possible to create a continuous flow with different cycle times at the workstations, by implementing the chaku-chaku principle, cf. chapter 2.2.4. The average takt time is the same as the central takt time of the assembly line. It allows different mix of engine variants without changing the line balance (takt time) by simply using more or less operators.

Figure 47 shows a scheme of the BMW chaku-chaku realized in an assembly line. The workers change workstations against the material flow, upstream, moving to the next free workstation. The high frequency of changing the workstations and the complexity of the work contents makes it necessary to have highly trained operators in a chaku-chaku loop. A downside of this mode of operation are additional walking times of the operators, but overall productivity may be increased.

Especially when the distribution of work content is restricted by assembly precedence and stationary mounting devices.

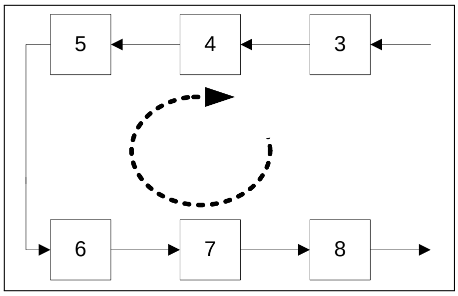


Figure 47.: BMW chaku-chaku scheme (cf. BMW Group, 2012)

Summarizing a line balance

Table 12 shows the scheme for a summary of a line balance. The available time is calculated by summing up the takt times of all workstations, which equals the number of workstations multiplied by the takt time. The available time is very important for the monitoring, as it represents the processing time in relation to the operators bound to takt. This example shows three workstations with a total cycle time of 2,562 minutes which represents the total workload incl. site-specific activities such as distance ranges or material handling. The takt balance is listed in minutes as well as in a percentage. This is traditionally used at BMW Steyr as an indicator for a well-balanced assembly line. Although the takt balance does not represent the amount of non-value added activities.

The potential is shown in number of workstations by dividing take balance with takt time. If the potential in workstations is greater than 1, the waiting times (takt balance) sums up to more than one takt. This represents a high possibility to reduce the number of workstations by redistributing the work content.

Workstations	3	#	= Number of workstations
Available time	2,836	min	= Number of workstations * Takt time
Total cycle time	2,562	min	= Amount of time for total work content
Total takt balance	0,274	min	= Time available - Total cycle time
Total takt balance	9,7	%	= Takt balance / Time available
Potential	0,3	#	= Takt balance / Takt time

Table 12.: Line balance - summary

3.2.4. Production preparation process

The production preparation process (3P) method described in BMW's Value-added Production System (VPS), partly uses concepts and ideas from Bortot (2009) and Mascitelli (2007). The associated term "Cardboard simulation" in the method represents a major part of the 3P-Process. The cardboard simulation is an economical and highly effective method, which is used in the Product Engineering Process (PEP), where high process impacts are possible with small efforts. It enables better planning for value-added production, manufacturing space and workstations. With simple means, repeated simulations are performed on-site to develop ideal processes on actual hardware. The simulations can be used for planning purposes as well as for improving or re-arranging existing workstations. Figure 48 shows a simulation made of wood and cardboard at BMW in Steyr.

Figure 48.: Cardboard simulation at BMW Steyr

In contrast to conventional planning methods, the cardboard simulation follows an "inside out" approach. The team starts with arranging an ideal process for work area and workstations. The operators (production worker) and foremen are involved in arranging of the workstations and apply their practical knowledge and experience. The production and logistics planning experts support the cardboard simulation. An important aspect is the determination of the workplace design according to a realistic, life-sized process simulation. The trial-and-error method of the production flow leads to practically oriented planning approach and an ideal production.

The target of the 3P/cardboard simulation is to design production areas and workstations according to VPS (avoiding waste), create a stable process for SOP ("do it right at the first time") and especially to avoid change costs in the start-up phase. Additionally a high acceptance due to active involvement of operators, as well as possibilities to test innovative concepts without interrupting the assembly operation are achieved with the cardboard simulation method.

The cross-functional core team consists of production and planner, operator, foreman and expert for VPS methods. The extended team members include specialists for quality, industrial engineering, occupational health and safety as well as ergonomics. It is also recommended to consult with representatives from the labor union.

Members of the core team are placed in workshops and are released from daily duties. The workshop lasts approximately two weeks, starting with a kick-off meeting and three days of a intense simulation phase. Necessary working material includes space, parts/components of existing or new product, containers, bins, cardboard boxes, wooden slats, tools and fastening material (duct tape, screws).

3.2.5. Using synergies from existing lines

There are two other assembly lines for modular kit engines at BMW. One is at the production site in Steyr assembling three-cylinder petrol and diesel engines, referred to as Line C. The other line (line D/E) is located in Munich assembling three- and four-cylinder petrol engines. These two assembly lines had SOP, 1 respectively 1,5 years ago and run in two shift operation during this thesis.

The line concept and the machines are very similar to assembly line B/G/E, as all modular kit engine assembly lines are based on the same reference system. The idea was to visit the assembly lines and talk to the experts, to generate ideas for assembly line B/G/E. The ideas included minor improvements concerning workplace design as well as possibilities for automation.

Workstation REM 130 in line E, illustrated in Figure 49, uses a corded handheld DPM code scanner after mounting the torsional vibration damper to the engine. An improvement in workplace design is implemented in the engine block assembly area in Line C, illustrated in Figure 50. By using a handheld cordless DPM code reader, it is possible to place it closer to the position where the DPM code is scanned during operation, indicated with the green arrow.

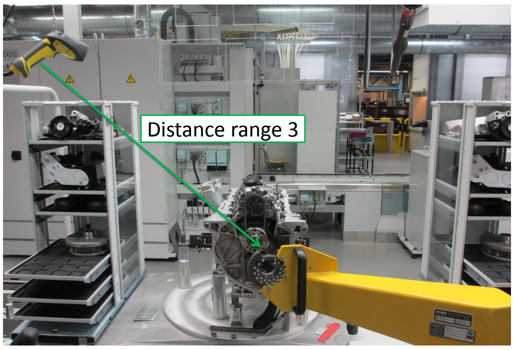


Figure 49.: DPM code reader at REM 130

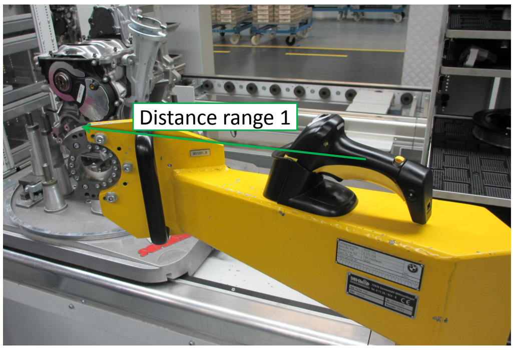


Figure 50.: DPM code reader at RCM 130

For REM 130 with the reader in distance range 3, the target time is 0,054 min and for RCM 130, using a cordless reader on a bracket at the stationary mounting device, in distance range 1 the target time is 0,032 min. The comparison of the target times between the two operations results in a difference of 0,022 minutes (0,022 min = 45 TMU / 1666,7 / 120%). Table 13 shows the difference in target times according to BMW standard data for this example. The investment for a cordless DPM code reader, including the bracket, would amount to about 3000 Euro.

REM 130		**RCM 130**	
Code	Target time	Code	Target time
S-ABE3	60 TMU	S-ABE1	30 TMU
S-PAE3	25 TMU	S-PAE1	10 TMU
Sum	85 TMU	*Sum*	40 TMU

Table 13.: Difference in target time for REM130 and RCM130

Figure 51 shows a DPM code scan of a part at workstation REM 310. A measure to decrease the processing time was found in line C as well in as line D. By installing a fixed-mount DPM code reader after the workstation, it is possible to eliminate the target time of 0,108 minutes, 0,054 min per scan, illustrated in Figure 52. This investment would sum up to approximately 47.000 Euro, as installed in line C and D.

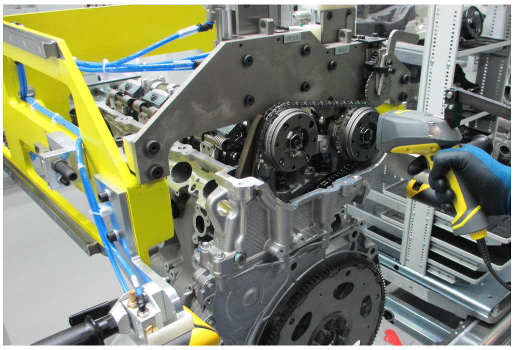


Figure 51.: Handheld DPM code reader REM 310

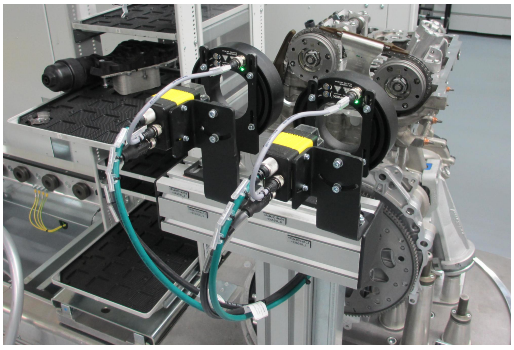


Figure 52.: Fixed-mount DPM code reader RCM 310

The visits in Munich of line D and E showed automated workstations as defined in the reference system. These workstations or operations were not automated in line B/G/E and selected examples are described in Sections 3.3 and 3.4.

3.2.6. Workpiece carrier release

The current means of releasing workpiece carriers (WPC) or electric monorail system (EMS) is either by pressing a release button or pulling a release line at the EMS. The standard target time for releasing is between 0,013 and 0,020 minutes, distance range 2 or 3.

Best practice solutions at BMW showed automatic solutions for WPC releases. One possibility is to use a laser sensor or pressure mat, and release the WPC when the operator leaves the workstation. This is very useful when implementing a BMW chaku chaku, as there is always a change between workstations. Additionally this way of releasing could be applied to workstations with longer walking distances. An existing BMW chaku chaku loop in Steyr shows good results with the pressure mats.

Another way of automatic WPC release is a DPM code scan or a screwing connection as defined last operation. In case of an "OK" signal from the PDM system to release the WPC, the system can automatically release the WPC. However this automatic way of releasing workpiece carriers has to be applied with caution. It requires stability over all product variants and special consideration of occupational safety.

One example for a stable application of an automatic WPC release is workstation FEM A10, pre-assembly for the exhaust turbo charger in the final assembly. An already installed laser sensor signals "OK" only when the the tray of the turbocharger is moved to the track for empty trays. As the laser sensor is already linked to the system, there would be no extra investment costs.

3.2.7. Innovations

An attempt to reduce the processing time is to apply handheld power screwdrivers with automatic screw feed systems in the assembly line, shown in Figure 54. The current way of screwing the pipes for the injection system to the cylinder head cover is with a normal electric power screwdriver and reaching for the screws separately. Figure 53 illustrates the current situation at workstation 530 of the engine block assembly for a B58 engine. The difference in target time for the screwing of two positions to the future state would be 0,085 minutes. For the B48 engine, which only requires one position, the difference would result in a reduction of the processing time of 0,035 min.

An external company is providing a test system and BMW will implement this handheld power screwdriver with automatic screw feeding system in the engine block assembly of line E. After a successful test, further screwing connections can be determined for this application. The investment cost for this system will be approximately 15.000 Euro.

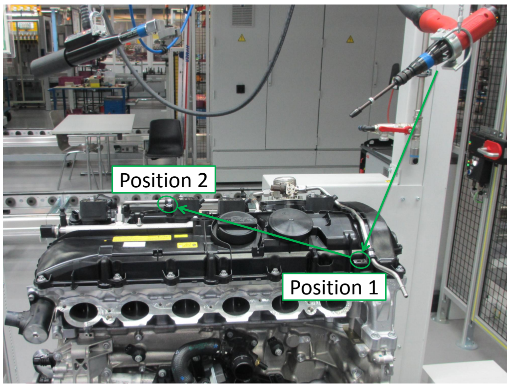


Figure 53.: Current situation REM 530

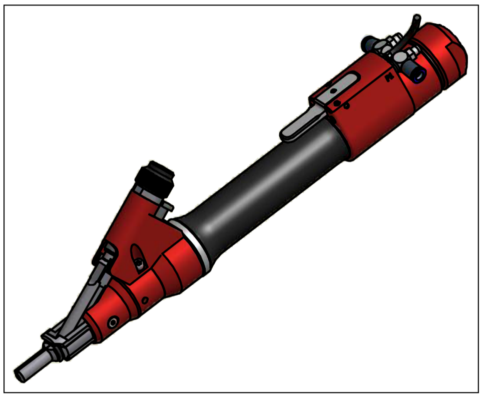


Figure 54.: Power screwdriver with automatic screw feed system [1]

A second device to improve productivity as well as process reliability, is a screw feeder supplying a specified quantity of screws. The operator uses a “soap dispenser” mechanism to get the screws and places them at the engine, illustrated in Figure 55. It is possible to eliminate counting, optimize reaching for screws, and throwing back remainder. Get-and-place a handful of screws according to BMW standard data amounts to 105 TMU in distance range 3, cf. Figure 42 . Specialists for industrial engineering at BMW evaluated savings of approximately one second (0,017 min) for mounting two or more screws.

The process reliability is improved, as all screws supplied by the device have to be assembled. The investment cost for a screw feeding device with soap dispenser mechanism is about 25.000 Euro.

Figure 55.: Screw feeder with soap dispenser mechanism

[1] Stoeger Automation GmbH, 2014

3.3. Cylinder head assembly

Line G is pre-assembling the cylinder head for the engine block assembly. With six manual and 18 automatic workstations, line G is highly automated. Figure 56 illustrates a very simplified (not to scale) layout of the cylinder head assembly. The assembly process starts at workstation ZGA 010 and ends at ZGA 290, where the cylinder head is transported into the buffer and is sequenced for the engine block assembly. The focus is on the manual workstations 170 to 250 in the manual loop on the lower right sector.

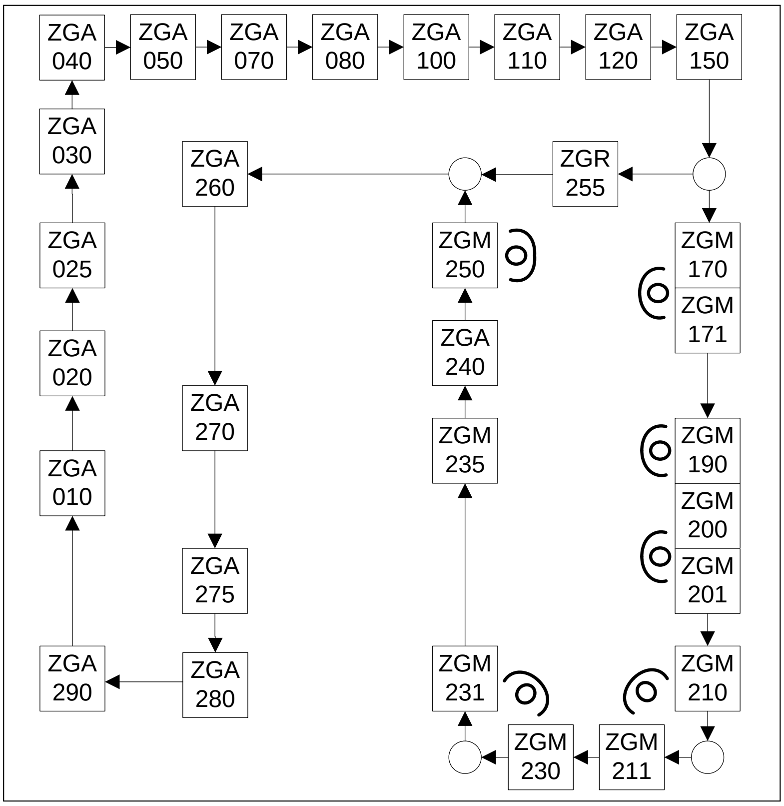


Figure 56.: Layout cylinder head assembly

3.3.1. Initial situation

The initial layout and the line balance of the manual loop in the cylinder head assembly, is illustrated in Figure 57 and the summary of the line balance is shown in Table 14. There are six workstations (= 5,670 minutes of processing time) with a total cycle time of 4,625 minutes which lead to a potential of 1,1 operators without assessing further potentials.

Workstations	6	#
Available time	5,673	min
Total cycle time	4,625	min
Total takt balance	1,047	min
Total takt balance	18	%
Potential	1,1	#

Table 14.: Line balance - summary

The operator mounts roller cam followers at the cylinder head and places two portable mounting devices, one on the cylinder head and one on the workpiece carrier, at 170. Then switches after every cylinder head to ZGM 171, where the eccentric shaft for the VVT is lubricated and placed in the cylinder head. The WPC then flows on to station number 190 where the operator mounts bearing brackets and screws them with a semi-automatic machine and a handheld power screwdriver.

Tasks at workstation ZGM 200 are mounting sliding blocks including screws which are screwed at station 201. The operator working at 210 and 211, first turns the actuator (DC motor) of the eccentric shaft to minimum position. Then mounts the return springs and places the second portable mounting device from the WPC. After pressing the release button the operator moves to ZGM 211 and uses the stationary device to tension the return springs.

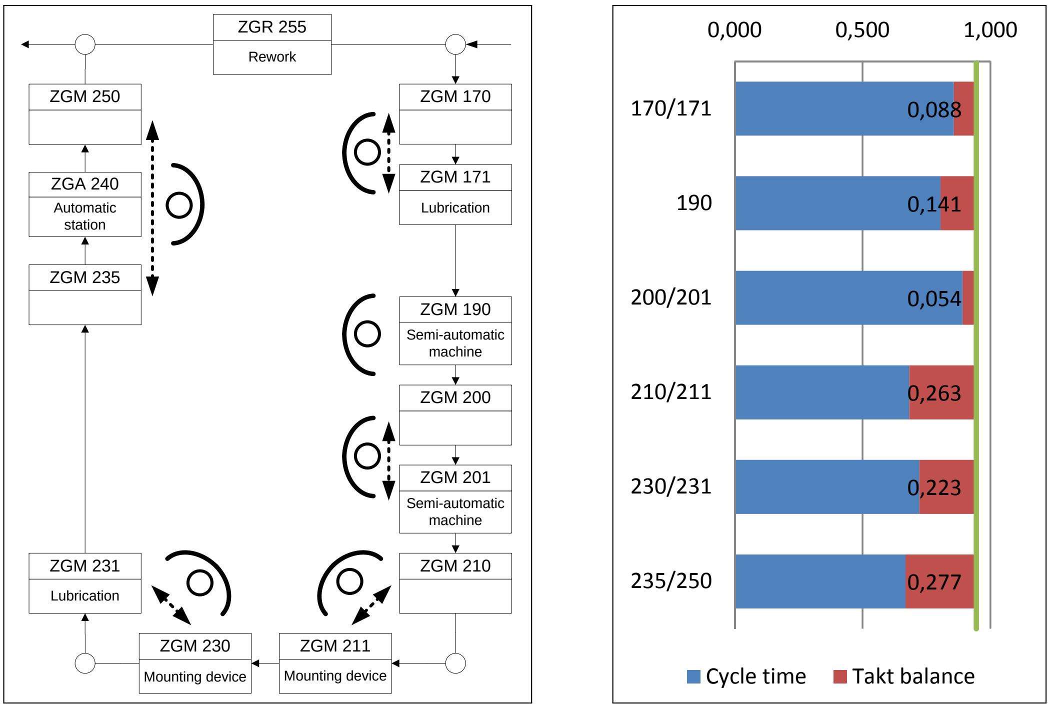


Figure 57.: Manual loop layout and line balance - initial situation

The operator at 230/231 first places the intermediate levers in the mounting device and then uses the device to place the lever in the cylinder head. After returning the mounting device to the initial position and walking to station 231, the operator lubricates the intake camshaft at the station and places it in the cylinder head.

Content for workstation 235 is mounting the bearing caps for the intake camshaft, which are screwed in ZGA 240. After every fourth workpiece, the operator walks to ZGM 250, takes the portable mounting devices down on a carriage and visually checks the return springs for correct positioning. Additionally the operator for 235/250 handles the carriages for the portable mounting devices. The work content of the manual loop in the initial line balance is listed in Table 15.

W/S	Parts and description
170	Place roller cam follower; Place portable mounting device (2x)
171	Lubricate and place eccentric shaft
190	Mount and screw bearing bracket (semi-automatic machine); mount and screw angular bearing cap (handheld power screwdriver)
200	Mount sliding blocks with screws
201	Screw sliding blocks with (semi-automatic machine)
210	Turn DC motor for VVT to minimum position; mount return springs; place portable mounting device
211	Tension return springs with stationary mounting device
230	Place intermediate lever on stationary mounting device; mount lever with device
231	Lubricate and place intake camshaft
235	Place bearing caps for intake camshaft
240	Screwing of bearing caps (automatic station)
250	Take down portable mounting devices; visual check for correct position of return springs; carriage handling for mounting devices

Table 15.: Work content and initial assembly sequence

3.3.2. Process analysis and line balancing

The assessment of potentials proved difficult, due to the early stage in the pilot production, although this gave a very good chance to learn about the process and discuss potential improvements.

Possibilities in the assembly sequence. The flexibility in the assembly sequence in the manual loop is rather limited, as most parts require operations at stationary devices. The possibilities are described as follows. The portable mounting device, which is mounted at ZGM 210, can be placed onto the WPC later than 170. The proximity of the carriage is the reason for the placement at workstation 170.

The bearing brackets are screwed with a stationary semi-automatic machine. The mounting operations can be performed after the placement of the eccentric shaft (ZGM 171) in the cylinder head and before ZGM 190. The angular bearing cap can also be mounted after the eccentric shaft. It is screwed after the bearing brackets at workstation 190, due to quality requirements. It can be mounted and screwed as well before turning the DC motor to the minimum position, whereas this operation must be completed at workstation 210. All operations of ZGM 235 can be performed at workstation 231.

Potentials. The WPC run-in times are mostly eliminated by operators switching between two workstations, except ZGM 190. Walking times have to be considered, but are significantly shorter than the run-in times.

Process times where operators are not bound are caused by the lubrication operation at workstations 171 and 231 and by the screwing operation with semi-automatic machines at workstations 190 and 201. These operations are waiting times and sources for parallelization. Process times of the screwing operation of the angular bearing cap, as well as turning the DC motor to minimum can be improved, because of the gap between planned and actual target times. The walking distance between ZGM 235 and 250 is identified as obvious waste and should be eliminated. Additionally the two portable mounting devices can be taken down simultaneously, which means multiple part handling and a possible target time reduction. Evaluation of the material handling situation was hardly possible due to non-serial operation status.

3.3.3. Implementing BMW chaku-chaku

Concrete measures derived form the potentials of the process analysis are moving the placement of the bearing caps for the intake camshaft from ZGM 235 to 231. In this way it is possible to utilize workstation 230/231 and at the same time eliminate the non-value-added activities of walking between ZGM 235 and 250.

The process time for lubrication of the eccentric shafts is 0,096 minutes. When moving the placement of the portable mounting device (target time = 0,070 min) on the WPC from workstation 170 to 171, the operator can use the process time of the lubrication to perform this operation. This makes it possible to mount the bearing bracket and the angular bearing cap for the eccentric shaft at workstation 171. Using the process time and moving the mounting operations, workstation 170/171 is utilized and there is a decrease in cycle time at ZGM 190.

The actualization of the process time of the handheld power screwdriver at ZGM 190, from 6 to 4,5 seconds, leads to a further decrease of 0,050 min for the two screwing connections of the angular bearing cap. The potential for turning the DC Motor to minimum position amounts to 0,033 min.

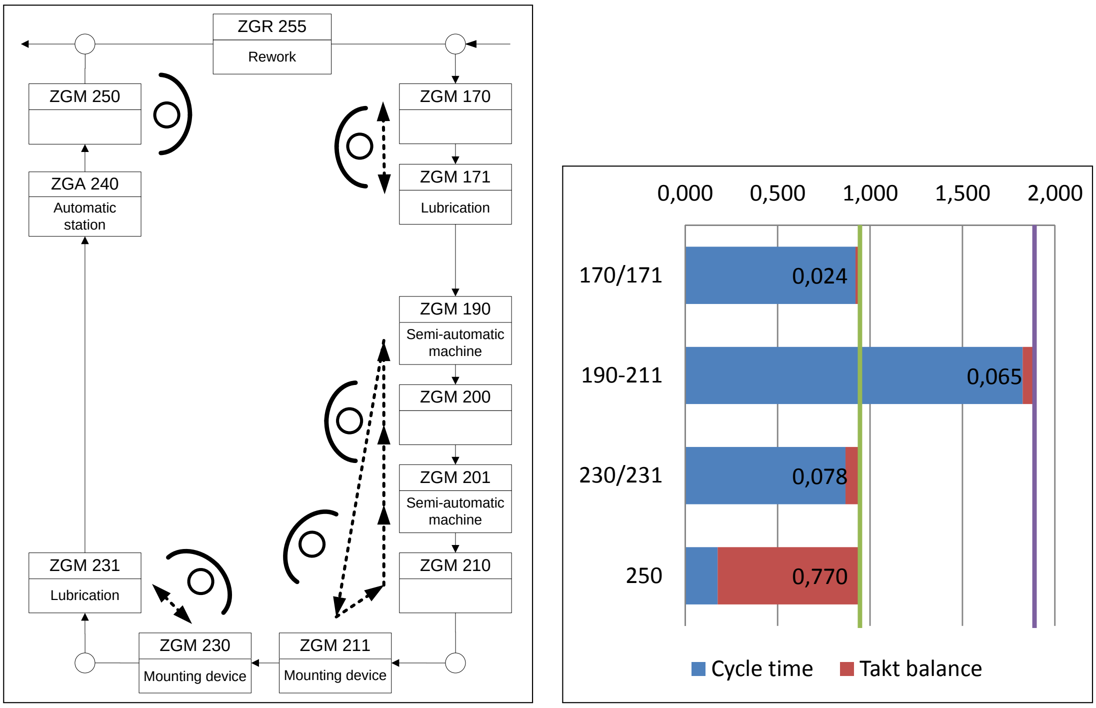


Figure 58.: Manual loop layout and line balance - BMW chaku-chaku

The remaining work content for ZGM 190 to 211 can not be moved to one or two workstations as to the fixed positions or anchors represented by the stationary mounting devices and the semi-automatic workstations. However by implementing the BMW chaku-chaku, according to Section 3.2.3 on page 65, it is possible to reduce the number of operators, illustrated in the layout on the left hand-side of Figure 58. The operators switch to the next free workstation upstream, after releasing the workpiece carrier. The additional walking distances of this operation mode can be accepted, due to the overall productivity increase.

The diagram on the right hand-side of Figure 58 shows the lean oriented approach of line balancing of the workstations. By concentrating the takt balance at workstation 250, it is easier to identify further possibilities for improvement. The operators for ZGM 190 to 211 have double takt time to complete all work contents. The diagram illustrates a line balance for a product mix of 60% B48 and 40% B58. This line balance is stable up to a mix of 46% B48 and 54% B58.

The BMW chaku-chaku mode can be implemented with low effort and costs, only the material handling situation has to be adapted in order to keep the walking distances as short as possible and clear the paths for the operators.

The summary of the line balance in Table 16 shows a decrease of the total cycle time from 4,625 to 3,789 minutes, which equals 20,2%. A total takt balance of 0,939 min still shows a potential of one workstation, mainly due to the high takt balance of workstation 250. It is not possible to remove the work content from workstation 250, that is why one operator is always tied to this workstation.

Workstations	5	#
Available time	4,727	min
Total cycle time	3,789	min
Total takt balance	0,939	min
Total takt balance	20	%
Potential	1,0	#

Table 16.: Line balance - summary

3.3.4. First automation

If there is no possibility for more work content, this workstation will be immensely underutilized. The combination of workstation 250 with 170/171 and redistributing work content is not possible at this point, as it would lead to over-utilization. However a further analysis after SOP in serial operation is recommended.

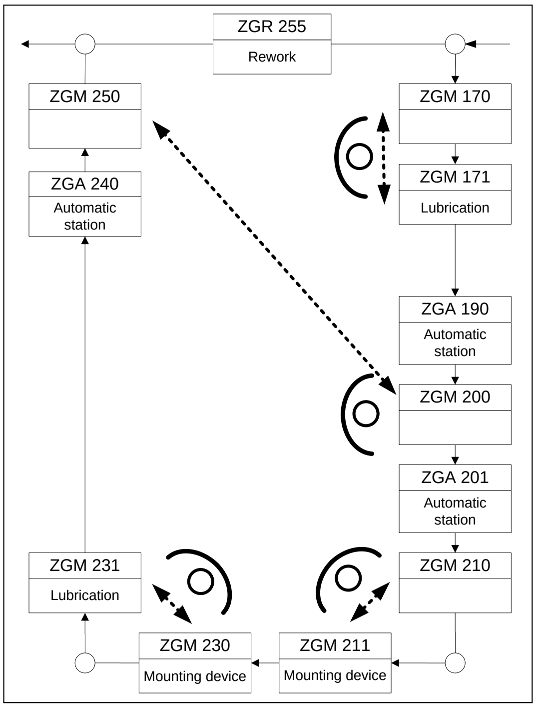
The next step in reducing the processing time of the cylinder head assembly is automation partly based on existing lines and the reference system. The cylinder head assembly in Munich has the same line concept and therefore the same manual loop, although the workstations 190 and 201 are fully automatized. In combination with a handheld multi power screwdriver instead of the angular power screwdriver for the angular bearing cap is useful in reducing processing time.

The full automation of ZGM 190 decreases the time by 0,220 minutes, and for ZGM 201 by 0,210 min, calculated for a product mix of 60% B48 and 40% B58. A multi power screwdriver reduces the time by 0,117 minutes.

The investment costs for these automations would be: 160.000 Euro for station 190; 30.000 Euro for station 201, as this workstation only requires horizontal adjustment by the operator. The multi power screwdriver would cost about 20.000 Euro, which was approximated together with the experts at BMW. The sum of investment costs would calculate to 210.000 Euro and lead to a total reduction in the cycle time by 0,547 minutes.

These automations clear the way for canceling the chaku-chaku from ZGM 190 to 211 and assigns one operator to ZGM 210/211 and one operator to 200 and 250, illustrated in Figure 59. The diagram in Figure 59 shows the multi power screwdriver placed in workstation ZGM 200 according to the lean oriented line balancing principle. To cover a product mix of 40% B48 and 60% B58 (or even more B58), it is recommended to place the multi screwdriver at workstation ZGM 210.

The long walking distances between ZGM 200 and 250 will be inevitable, as long as the work contents at ZGM 250 have to be performed manually. The distances are accepted, because of the possible operator reduction in the manual loop.



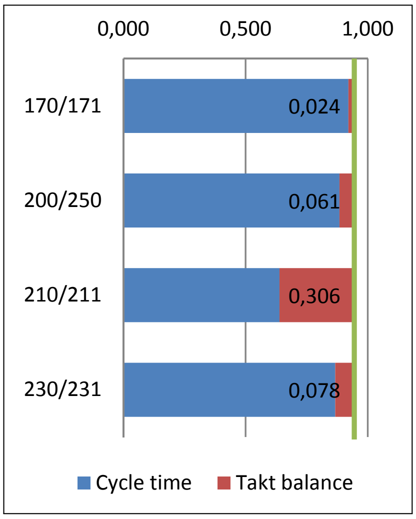


Figure 59.: Manual loop layout and line balance - first automation

The processing time can be lowered from 3,789 to 3,312 minutes, illustrated in Table 17. This amounts to 20%, and the cycle time is decreased by 12,6% compared to the scenario with five operators. The 0,547 minutes from the investment were not fully exhausted, due to the additional walking distance between workstation 200 and 250.

Workstations	4	#
Available time	3,782	min
Total cycle time	3,312	min
Total takt balance	0,470	min
Total takt balance	12	%
Potential	0,5	#

Table 17.: Line balance - summary

3.3.5. Outlook

A possibility to untie the operator from workstation 250 is to further invest in automation. This would require an automatic station to take down the portable mounting devices, one to transport them to workstation 170/170 and a camera station to visually check the return springs for correct positioning.

After discussions with the production planning experts at BMW the costs for the camera station and the conveying equipment would sum up to over 300.000 Euro. Concepts for these stations are already existing and currently under inquiry. A concept for an automatic station to take down the portable devices is not yet clear and it was not possible to get an estimate on the investment costs. The camera station would bring a reduction of 0,072 min, the conveying equipment 0,047 min and the automatic removal of the mounting devices 0,153 minutes.

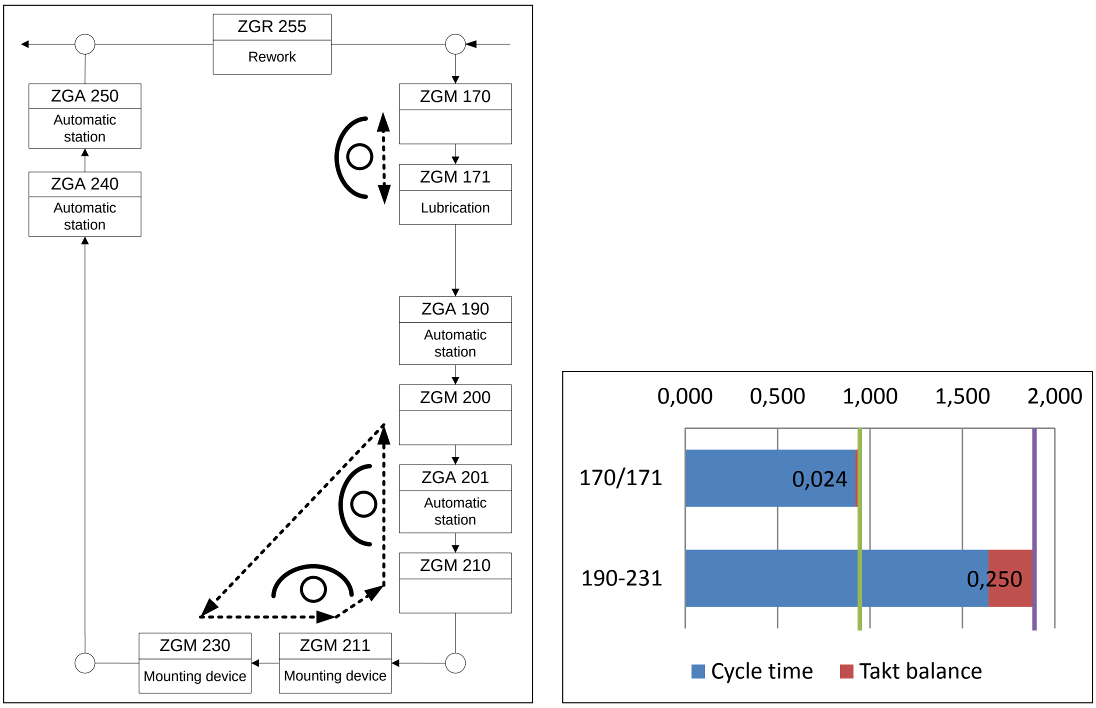


Figure 60.: Manual loop layout and line balance - outlook

An automatic station included in the reference system and therefore in line F in Munich is a fully automated station for the assembly of the intake camshaft, including the bearing caps. This automatic station would lead to a reduction of 0,475 minutes of processing time, although an estimation of the investment costs amounts to 1.250.000 Euro.

Figure 60 illustrates the layout with another introduction of the BMW chaku-chaku mode. Two operators move against the WPC flow to the next free workstation. With only minor redistribution of mounting the angular bearing caps after ZGM 171, this layout works for a product mix of 40% B48 and 60% B58 as well.

These investments would lead to another direct productivity increase with a reduction of one operator. The reduction to 2,562 min in total cycle time, shown in Table 18, calculates to 22%. Important to mention is the decrease of the takt balance to 0,274 min of the takt time. At this point in time, the investment costs are too high and would not justify the related productivity increase.

Workstations	3	#
Available time	2,836	min
Total cycle time	2,562	min
Total takt balance	0,274	min
Total takt balance	10	%
Potential	0,3	#

Table 18.: Line balance - summary

3.4. Engine block assembly

The engine block assembly is part of the main assembly line and is very complex with 18 automatic and 24 manual workstations. The start of the engine block assembly is the engraving of the engine identification number onto the short block and followed by elevating the workpiece carrier to the main line. The first automatic station REA 060 illustrated in Figure 61, presses in a rotary shaft seal into the short block.

The engine is placed upside-down on the WPC with the combustion chamber on the bottom. Operators at REM 080 to 130, further addressed to as group 1, mounts and assembles several sensors, parts of the chain drive, such as chain, guide rails, chain tensioner; as well as the baffle plate (windage tray), oil pump, oil suction pipe, fitting sleeves and torsional vibration damper. The screws for the baffle plate and the oil pump are automatically tightened at station 180. The operator at workstation 200 places the rear cover into the automatic station 190. After automatic sealant application, the operator mounts the rear cover.

The automatic workstations 210 and 220 tighten the rear cover and torsional vibration damper. The operator at REM 238 places the oil sump at a WPC, mounts and tightens an oil level sensor. Station 240 applies a sealant to the oil sump and places it on the crankcase. The oil sump is tightened at REA 250 and the crankcase is rotated so combustion chambers are at the top (REA 260). The operator at REM 265 places the cylinder head gasket and mounts the knock sensors to the crankcase.

REM 268 is the pre-assembly for automatic station REA 270, which is placing the cylinder head on the engine block. The cylinder head and the crankcase are screwed together at station 281. The operator at REM 287 places the flywheel, including screws, on a workpiece carrier for station REA 290, which is automatically tightened to the engine block.

Group 2, REM 310 to 350, starts with assembling the actuators for the VVT, called Variable camshaft control (VANOS), and positions the camshafts with a stationary mounting device. The DPM code scan operation for REM 310 is illustrated in Figure 51. Further parts assembled in this group is the cam sensor wheel, rails for the chain drive, the acoustic elements for B48, the mounting foot, the aggregate bracket, the oil filter, the heat management module and connecting elements like tubes. The automatic station REA 380 sets and adjusts the valve timing of the engine. An operator at REM 390 places the cylinder head cover and assembles the upper chain tensioner. The automatic workstations REA 400 and 410 tighten the cylinder head cover, the heat management module, the oil filter, the aggregate bracket and the mounting foot for the engine.

An operator inserts fuel rails and injectors at REM 415 for the automatic placement of REA 420. REM 430 to 530, group 3, mount magnetic actuators for the VVT, camshaft sensors, high-pressure pump, including pipes, ignition coils and customer label. The automatic station in group 3, REA 510 tightens the high-pressure pump and injectors. The engine has to pass a leak test before moving on to the final assembly.

3.4.1. Initial situation

The initial line balance is not leveled as illustrated in Figure 62. In some workstations the cycle times are higher than the takt time, mostly due to pilot production status and pending changes concerning design and purchased parts. Other workstations are underutilized.

Table 19 shows a total takt balance of 7% which is evaluated as good. However serial operation is not possible with this unbalanced distribution of work contents. It is challenging to utilize the potential of 1,8 operators, due to the high number of workstations and the complexity of the assembly sequence. But there are many potentials in the initial line balance.

Workstations	24	#
Available time	22,691	min
Total cycle time	21,028	min
Total takt balance	1,663	min
Total takt balance	7	%
Potential	1,8	#

Table 19.: Line balance - summary

3.4.2. Process analysis and line balancing

The process analysis for observing the 24 manual workstations took multiple weeks to complete. During the extensive analysis of the operations on-site, which are necessary to assemble over 50 different parts to the engine block, possibilities in the sequence of assembly were studied. Various discussions with foremen were used to evaluate the assembly position in regards to ergonomics, quality requirements and therefore, the optimum workstations for parts to be mounted. Technical assembly requirements were also discussed with specialists from the development department to ensure conformity.

The focus for the line balancing process was on utilizing workstations on the main line, which are most inflexible regarding the redistribution of work content. These are workstations between automatic workstations and have strict restrictions of parts to be assembled. Due to the utilization of the these workstations, the redistribution of work content in the groups 1, 2 or 3 possibly allow a reduction of workstations in the groups. The goal was to find parts that can be assembled, or operations that can be performed at workstations 200, 265 and 390.

Further aspects of line balancing are to minimize the cycle time spread in order to create stable work cycles. This requires the identification of parts or operations, that are only needed for one engine variant and combine parts or operations performed on other engine variant, at one workstation. The same is true for combining same or similar parts of derivatives at the same workstations. Stable work cycles build the basis for a stable line balance regarding changes in the product mix.

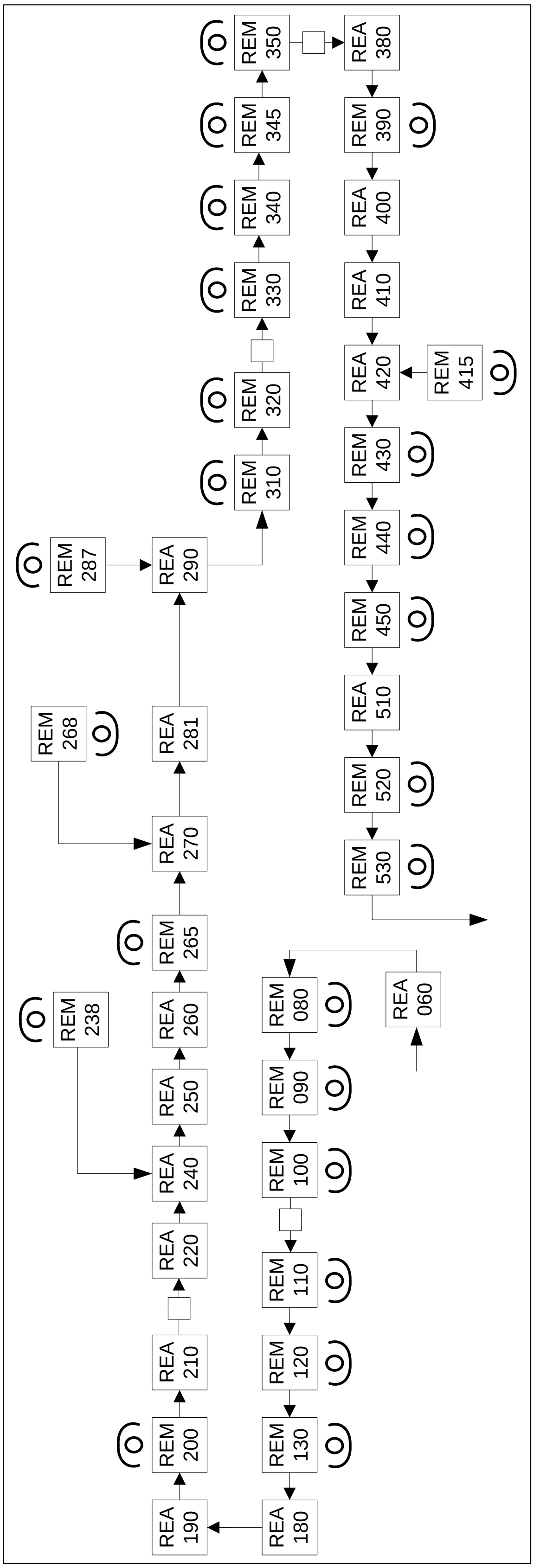


Figure 61.: Layout engine block assembly

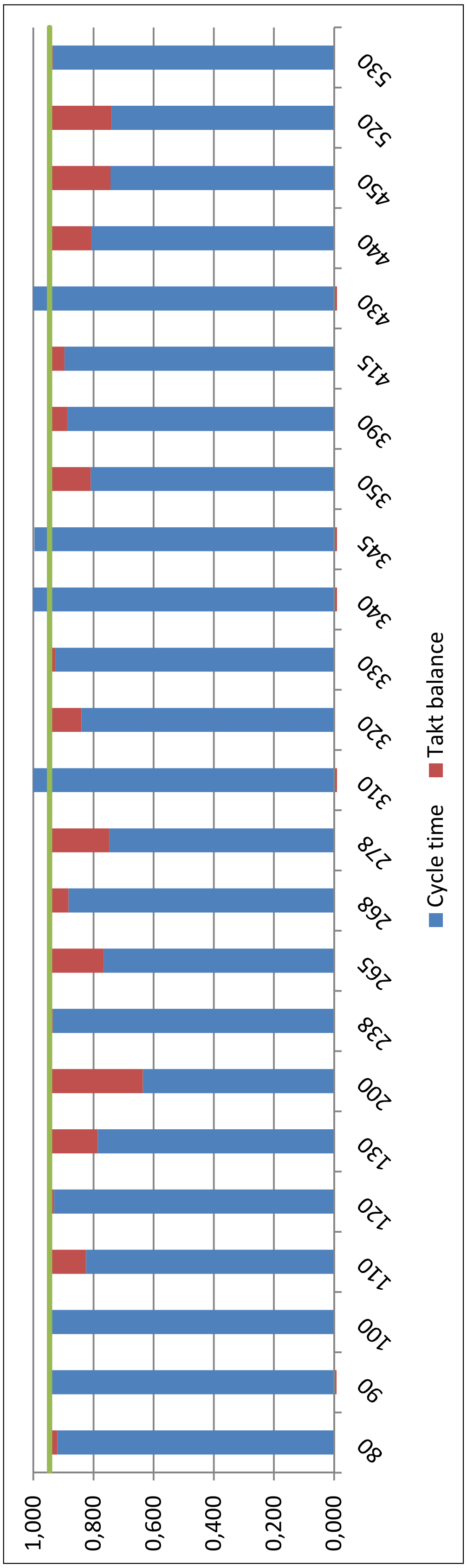


Figure 62.: Engine block assembly - initial line balance

Lean oriented line balancing is applied as well; by utilizing workstations to a maximum it is easier to identify further potentials. To increase in-process reliability for assembling parts, mounting and final tightening operations should be performed at the same workstation. However a maximum of two final tightening operations should be moved to one workstation to avoid tool changes.

Possibilities in the assembly sequence. The first step in finding possibilities for redistributing work contents is to define engine position and line height for the parts to be assembled. The height of the assembly line is categorized into *high*, *middle* or *low*. The line height for workstations 080 to 100 is high, middle for 110 to 210, low for workstations 220 to 320, for REM 330 to 350 middle and for 380 to 530 the height is low. The lifting tables in the layout are indicated with small white squares between the workstations, cf. Figure 61.

The engine positions are defined as *intake* for parts assembled on the side of the intake ports and respectively *outlet*, for parts mounted on side with outlet ports. Parts requiring the engine position for the torsional vibration damper will be be defined with *TV-damper* and parts on the side of the power output or gearbox such as flywheel, will be defined as *flywheel*.

Table 20 shows selected parts of the engine block assembly that are important regarding the line balance of Section 3.4.3 and 3.4.4. There is a special focus on parts for utilizing workstations 200, 265 and 390. The table describes the parts with necessary line heights and engine position; combined with restrictions in the sequence of assembly, it is possible to define suitable workstations for mounting the parts.

Part	**Line height**	**Engine Position**	**Suitable workstations**
Lower chain tensioner	high, medium	flywheel	REM 080 - 200
Oil suction pipe	medium	flywheel	REM 110 - 200
Knock sensor	medium, low	intake	REM 265 - 345
Cooler connecting piece	all, (low)	intake	REM 265 - 345
Water temperature sensor	all	intake	REM 265 - 345
Guide rail	medium, low	flywheel	REM 310 - 390
Slide rail	medium, low	flywheel	REM 310 - 390
Oil-pressure sensor	all	intake	REM all
Connecting piece (B58)	all	TV-damper	REM all

Table 20.: Selected parts of the engine block assembly

The lower chain tensioner requires three operations: mounting, including screws with first tightening; final screwing, with power screwdriver and unlocking the tensioner by removing the pin. The lower chain tensioner can be mounted after the lower chain, which is mounted at REM 090. The best line height for mounting is high, although final tightening and removing the pin can be performed at workstation up to REM200.

After placing the oil pump (medium height; REM 110-130), the oil suction pipe can be mounted, screws can be put in and the final tightening operation can be performed. As the oil suction pipe needs to be assembled before the oil sump, the last manual workstation is REM 200 for performing these operations.

The knock sensors can be assembled after the turn of the crankcase (REA 260), as they require a mounting gauge, which would be blocked by the WPC before workstation 260. Furthermore the sensors need to be mounted, but not tightened, before the cooler connecting piece and the aggregate bracket. These precedence restrictions make an assembly possible from manual workstation 265 to 345 .

The cooler connecting piece and the water temperature sensor should be mounted at the same workstation in order to create a stable work cycle, which is not the case in the initial line balance. An additional reason for assembling both parts at the same workstation, is that the order of assembly is different for four- and six-cylinder engines. For the B58 engines the cooler connecting piece needs to be tightened first, and then the water temperature sensor. B48 engines require mounting and final tightening operation of the sensor first. Both parts need to be assembled after the knock sensors and before the oil filter (345/350).

The guide rail and the slide rail require a medium or low line height. Both require a mounting operation with placement of screws and a final tightening operation. For the guide rail, both operations should be performed at the same workstation. After discussions with a development specialist, both rails are identified for assembly at REM 390. Both rails need to be assembled after the VANOS actuators at REM 310 and before placing the cylinder head cover onto the engine at REM 390.

The oil-pressure sensor is identified as suitable for all manual workstations and requires the engine at intake position. This part also requires a mounting and final tightening operation. The last part listed in Table 20 is the connecting piece is only assembled on the B58 engines, and requires TV-damper position of the engine. This makes the part suitable for assembly at REM 130, but at the same time can, be used to eliminate possible cycle time spread.

3.4.3. Line balance proposal

The description of the line balance proposal will be limited to utilizing the selected workstations and incorporating the line balancing principles, because of the magnitude and complexity of the line balance.

Utilizing workstations 200, 265 and 390. The information about the possibilities in the assembly sequence gained from the analysis can be used as follows:

The final tightening operation for the lower chain tensioner, as well as all operations of the oil suction pipe are moved to workstation *REM 200*, cf. Table 20. With these operations, the maximum of two final tightening operations is reached. It is possible to utilize 0,136 minutes of the WPC-run-in time by getting and placing the rear cover in the automatic station, as well as pulling out the drawer from the engine set. This leads to a takt balance (idle time) of only 0,080 minutes, with a productive time of 92% at this workstation.

Parts being mounted at *REM 265* are cylinder head gasket and knock sensors. Moving the oil-pressure sensor, mounting and final tightening operation, to this workstation makes a 98% utilization possible. However only 0,020 minutes of the run-in time are used in this case, which makes it necessary to define further operations to perform during the run-in time.

Workstation *REM 390* shows a huge potential in actualization of the current performed operations. Moreover screwing operations which are currently necessary due to quality reasons, should be eliminated by SOP. With utilizing 0,085 minutes of the run-in time, material handling not yet considered, and moving all slide rail operations to 390, the takt balance amounts to 0,175 minutes. The operation for the final tightening of the guide rail would be possible, but as described in Section 3.4.2, should be performed at the same station as mounting. Also the maximum of two final tightening operations is already reached at this workstation, which makes an additional tool change necessary. Currently there is no socket magazine available at REM 390, also due to space limitations.

The goal is to move the operations for the guide rail to workstation 390, and remove the ventilation nozzle for the cylinder head, also due to ergonomic reasons, and the roller valve tappet. Currently this is not possible, but should be considered for future line balancing.

Creating stable work cycles. A stable work cycle is reached, when operations required for both engine variants are approximately the same. To give an example of this concept of creating stable work cycles, selected parts are described. This means, that there is almost no spread between variants and mixed times. (cf. Figure 37). The required times, including necessary WPC turns, for these parts are listed in Table 21.

Part	B48	B58
Heat management module	0,433 min	0,236 min
Connecting tube (B58)	-	0,183 min
Acoustic element (B48)	0,330 min	-
Connecting piece (B58)	-	0,363 min

Table 21.: Selected parts with target times

The heat management module for B48 needs TV-damper position and therefore two times 90° turns, compared to the B58 at inlet position. To create a stable takt, the workstation assembling the heat management module for both B48 and B58, need additional operations only performed for B58. Operations necessary for the connecting tube for B58 between the heat management module and the cooler connecting piece, fits perfectly to create a stable work cycle. The target times for the operations at the workstation for B48 is 0,433 minutes and B58 is 0,419 min (=0,236 + 0,183) results in a very stable work cycle, which is almost the same for both variants.

The same target of creating a stable line balance is reached by combining the acoustic element for B48, assembled at workstation REM 330 and the connecting piece for B58, assembled in group 3. The cycle time spread between these two parts is minimal, 0,330 min for B48 compared to 0,363 min for B58. At the same time the combination all of the operations for the connecting piece (B58) at one workstation avoids two 90° turns, which are performed in the initial line balance.

Using identified potentials. The identified and incorporated potentials for the engine block assembly is listed in Table 22. By updating the existing operations and the process times of the power screwdrivers of the initial line balance, it is possible to reduce the processing target time in the amount of 1,056 minutes.

The total WPC run-in times sum up to 3,841 minutes, cf. Table 9. The operations performed in the run-in times are 1,595 minutes which only makes 42% of the total waiting time and can be further utilized. By redistributing the final tightening operations, it is possible to avoid tool changes. In this case the number tool changes are reduced from three to two. The reduction of the number of workstations is in contrast to avoiding tool changes.

Potential	**Time**
Update existing line balance	0,766 min
Update process times for power screwdrivers	0,290 min
Utilize WPC run-in times	1,595 min
Avoid tool changes for power screwdrivers	0,063 min
Avoid workpiece carrier turns	0,102 min
Optimize workstations	0,022 min
Simple automation	0,055 min
Sum	**2,893 min**

Table 22.: Potentials used

The WPC turns were reduced by two, which amounts to 0,102 min in total. There are still 15 turns performed in the engine block assembly and with further optimization, even more potentials can be gained. The optimization of workstations was not considered to a large extent, due to the necessity of iteration between operations and line balance, cf. Section 3.2.3. The example incorporated is described in Section 3.2.5, decreasing the distance range of a DPM code reader and gaining 0,022 minutes.

Furthermore, the use of an innovative handheld power screwdriver with automatic screw feed system, leads to a reduction of 0,055 minutes for 60% B48 and 40% B58 engines. More details for this innovation in an assembly line at BMW Steyr is described in Section 3.2.7.

Summarizing the line balance. Figure 63 shows the result of the line balance incorporating the utilization of workstations 200, 265 and 390 and the stable work cycles. It is possible to close two workstations in group 1. Figure 63 illustrates REM 080 and 120 with 100% takt balance, which in this case refers to being closed. REM 080 represents a workstation with line height high and REM 120 with line height medium.

Workstations 340 with line height medium and 440 with line height low are also able to be closed. The work contents are moved to workstations within the respective groups. The pre-assembly workstations 287 and 415 are not well utilized, because of the difficulty in integrating or moving work content from the main line to these workstations.

Workstations	20	#
Available time	18,909	min
Total cycle time	17,036	min
Total takt balance	1,873	min
Total takt balance	10	%
Potential	2,0	#

Table 23.: Line balance - summary

This line balance proposal leads to a reduction of 4 workstations which equates to 3,780 minutes of processing time for the engine block assembly. Effort and expenditure are comparable to a regular redistribution of work content (line balance) in other assembly lines in Steyr. It requires changes for the installed lubrication systems, power screwdrivers, DPM code readers and flow racks for the parts.

A takt balance with 10%, shown in Table 23, is evaluated as good. However if the takt balance of the pre-assembly workstations (REM 238, 268, 287, 415; total takt balance equals 0,840 min) is not considered, the takt balance of the main line is 5%, equals 1,033 min, and hence very good! The goal of course is to utilize all idle times in order to increase productivity.

3.4.4. Line balance with first automation

The line balance for this scenario with first automation is shown in Figure 64. The screwing connection tightened at REM 100 are automated. Four bolts for guide and tensioning rails, two screws for the lower chain tensioner, the screw for the sprocket wheel and the workpiece carrier run-in time amount to a total time of 0,761 minutes compared to the initial line balance. In

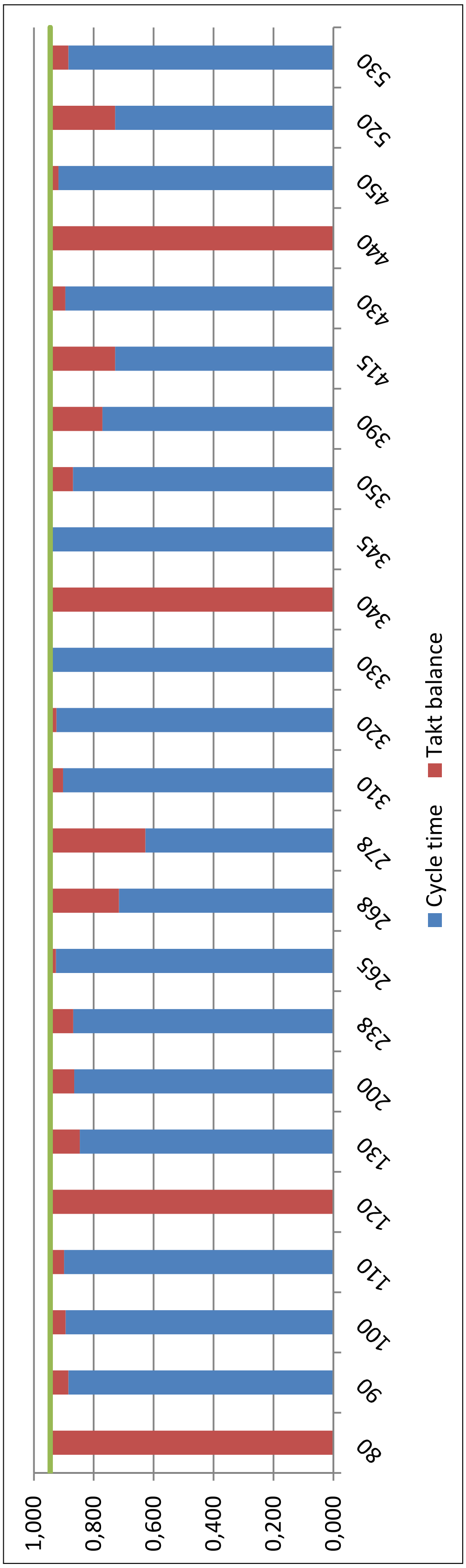


Figure 63.: Engine block assembly - line balance proposal

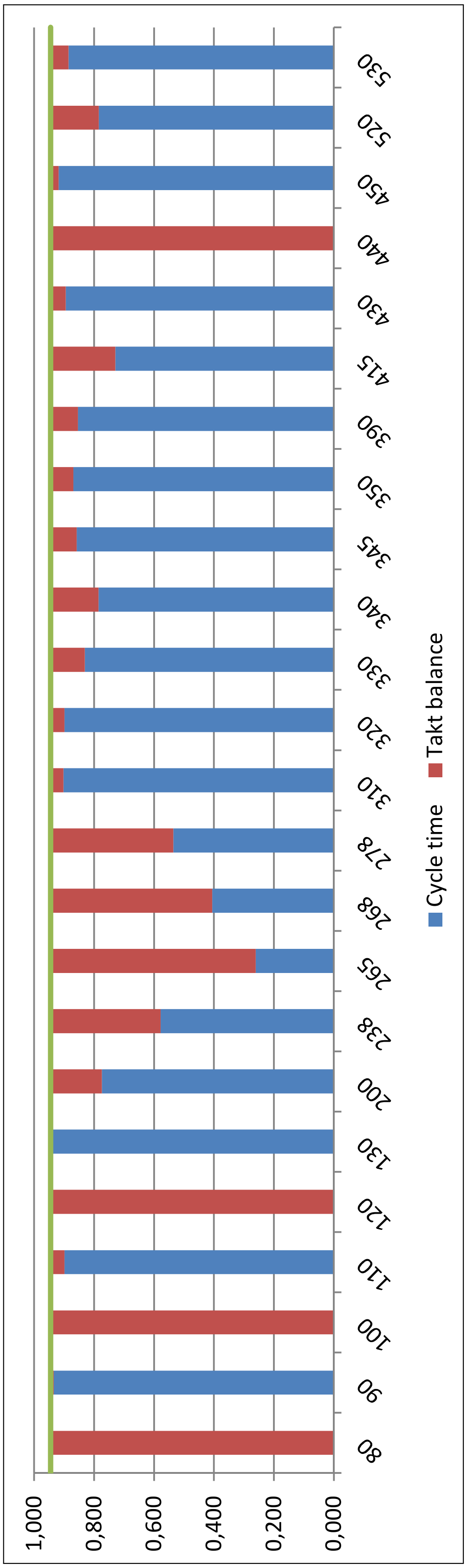


Figure 64.: Engine block assembly - line balance with first automation

combination with moving the fitting sleeves, 0,183 min, from the engine block assembly to the short block assembly, or installing an automated workstation, this results in the possibility for a reduction of one workstation in group 1. This investment of automating both is approximately 500.000 Euro and will result in a direct productivity increase.

The operator at workstation REM 238 needs to perform three operations for the nuts of the oil level sensor: placing the nuts, first tightening operation with a defined torque and a final tightening operation with a different torque which requires a different power screwdriver. The visit to Line D in Munich showed an automatic station that performs these two tightening operations automatically which result in a decrease of 0,270 min. A stationary automatic DPM code reader reduces the target time of another 0,054 minutes. The investment cost for this automation would be 265.000 Euro.

This investment would make it possible to combine the workstations 238 and 265. The walking distance of 10 meters would lead to a predetermined time of 0,125 min which would eliminate the complete run-in time of the workpiece carriers. A major drawback concerning productivity is switching waiting time (run-in time) for walking (non-value-added activity) and the necessity to move the work content from REM 265 to group 2, REM 310 to 350. All work content except the cylinder head gasket and related operations: knock sensors and oil pressure sensor both equal to 0,498 minutes, would be assembled downstream and force a workstation to be opened. The investment and the combination of the workstations would only decrease the total cycle time, and not result in a direct productivity increase.

The disadvantage with moving work content along the main line does not happen when combining the pre-assembly workstations 268 and 287. In the initial line balance, an operator at REM 268 places washers on screws and then in the cylinder head. By supplying screws with washers or automating the placement of the washers on the screws, this would lead to a reduction of 0,435 minutes of cycle time.

Workstation 287 places flywheels and transmitter wheels, including screws, on workpiece carriers. Flywheels for automatic transmission require 0,091 minutes, which can be reduced to 0,041 when moving the material closer to the workstation and therefore eliminating walking distances. For double-mass flywheels, for manual transmission, a chain hoist is required. The predetermined time according to the initial line balance is 0,434 min with an assembly rate up to about 25% compared to automatic flywheels. With an optimization of the hoist, additional potential can be used; the potential was not assessed during the thesis.

These described measures make it possible to combine the workstations REM 268/287. Walking distances of 10 meters make it possible to eliminate the WPC run-in times. With 25% manual transmission the takt balance of the combined workstations is close to 0%, which utilizes them to takt time. Although with an increase in B58 engines the takt balance will increase, as they mostly require automatic flywheels.

Table 24 shows the summary of the line balance with 18 workstations after implementing first automation and combining the workstations REM 238/265 and 268/287. As discussed, the investment for REM 238 does not lead to direct productivity improvements, but decreases the total cycle time. Whereas automation of the screwing connections of REM 100 and the fitting sleeves, as well as a solution for the washers at the screws at station 268, lead to a direct productivity increase of two operators. The total takt balance was reduced, but now additional walking distances are performed, which represent non-value-added activities.

Workstations	18	#
Available time	17,018	min
Total cycle time	15,541	min
Total takt balance	1,478	min
Total takt balance	9	%
Potential	1,6	#

Table 24.: Line balance - summary

Further automation possibilities not yet considered in this line balance, are shortly described as follows. A fixed-mount DPM code scan, cf. Figure 52 in Section 3.2.5, among other DPM code scans for parts were not implemented, due to the decreasing flexibility in line balancing. DPM code readers for process reliability purposes, have to be installed at workstations of assembly which therefore, restricts the possibilities or increases costs of line balancing.

The assembly of the rear cover at REM 200 can as also automated for approximately 1.700.000 Euro, estimated with investment costs of a similar workstation. This would only reduce the cycle time by 0,357 minutes and the remaining work contents would have to be performed in group 1, which is very well utilized and would require an additional workstation.

A multi power screwdriver or a fully automated station for screwing the ignition coils, could be automated in combination with pressing the coils in the engine, as well as reading the DPM code of every ignition coil. There is no mounting device installed and no necessity to read DPM codes in the initial line balance, and therefore makes it difficult to evaluate.

There are 17 manual WPC turns, not to be confuse with turning tables, in the initial line balance. It would be reasonable to install possibilities for automatic WPC turns before manual workstations. The investment costs for one automatic turning device would be approximately 25.000 Euro.

3.5. Final assembly

After the leak test in the engine block assembly, the engine is transported to the final assembly, where it is first swapped from the workpiece carrier to an EMS, illustrated in Figure 35 at page 43. The EMS makes an automatic height adjustment at every workstation possible, an ergonomic working height can also be set for different engine variants.

The layout of the final assembly is shown in Figure 65. Just before workstation FEM 060 the engine set is filled by logistics. Operators at workstations 060 to 080 assemble heat protection sheets, acoustic elements, temperature sensors and a gasket for exhaust ducts.

The pre-assembly for the turbocharger is run by three operators. One on FEM A10 picking up the turbocharger which is sequenced by logistics and two at FEM A31 and A32 assembling and screwing the connecting pipes. The turbocharger is mounted to the engine at REM 090. The operators switch the workstations as indicated by the arrows in the layout in Figure 65.

The work contents of workstations 100 to 130 are mounting oil/water pipes, clips for tubes, automotive wiring harnesses, as well as connecting them to parts such as knock sensors and oil filter. Operators at these workstations also assemble brackets and holders for the water pump, intake system and other parts. One operator at FEM 140 mounts the intake system with the throttle valve, which is pre-assembled by an operator at FEM S20.

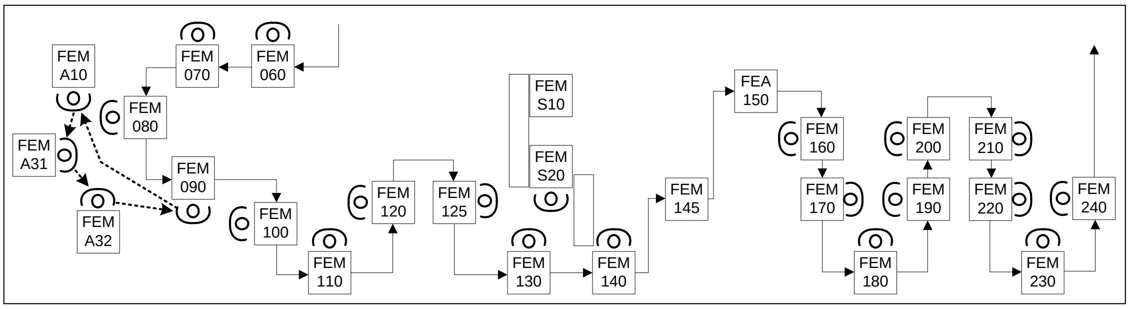


Figure 65.: Layout final assembly

The only automatic station, FEA 150, screws the exhaust turbocharger and the intake system to the engine block. Followed by the workstations 160 to 240 which assemble heat protection sheets at the outlet side of the engine and more automotive wiring harnesses such as a harness for the sensor system. They tighten parts with screws, connecting harnesses with parts and sensors and place wires and tubes in the correct positions. An operator at the last workstation checks several plugs for the correct connections, before the engine is transported to the end-of-line-test.

Table 25 shows the summary of the initial line balance with 23 workstations. The takt balance of 2,725 min shows a huge potential of 2,9 takt times.

Workstations	23	#
Available time	21,745	min
Total cycle time	19,020	min
Total takt balance	2,725	min
Total takt balance	13	%
Potential	2,9	#

Table 25.: Line balance - summary

3.5.1. Process analysis

The process analysis in the final assembly was primarily performed during two performance tests in the pilot production. These performance tests were executed with only half the operators and only 90 to 105 engines, which made it difficult to identify waste and potentials. This is why the operators would switch between two workstations and not efficiently focus on one workstation. The second approach for identifying potentials in this area was to actively be present in the assembly area and as well, build engines.

Potentials listed in Table 26 are according to Section 3.2.2. Updating the existing line balance can bring 0,327 min. This contains extra operations which are not performed or not needed, such as walking distances for changing to the other side of the EMS. The process times in the assembly area can decrease by 0,780 min, when updating from the initial situation.

Additionally in this area, the operators have to make a release order for replenishment of materials and parts. The release orders at the terminals to trigger replenishment of the parts, should be automatically generated by either using a counter or an electronic kanban system. The cycle time can be decreased by 0,145 min.

The optimization of workstations in terms of using cordless power screwdrivers for initial tightening of screws instead of a normal screwdriver would decrease the cycle time by 0,033 min. This is currently not possible, because of the screws used. Further optimization for the reach area of tools and materials has to be assessed in serial operation.

A simple automation option for the carriages of the turbochargers at workstation FEM A10 is possible. To receive an "OK" signal from the system for releasing the carriage, the operator has to remove a tray. In this case all the hardware is already installed and the system could automatically release the carriage which would result in a decrease by 0,020 min of the cycle time.

There is no line balance proposal, therefore the potentials were analyzed with production experts at BMW. With the current takt balance of 2,725 minutes and the identified potentials of 2,237 min it is possible to reduce three workstations in the final assembly.

Potential	Time
Update existing line balance	0,327 min
Update process times for power screwdrivers	0,780 min
Utilize EMS run-in times	0,932 min
Optimize workstations	0,033 min
Simple automation	0,020 min
Release order for replenishment	0,145 min
Sum	**2,237 min**

Table 26.: Potentials identified

Due to frequent changes in the layout, including a modification in the EMS system the focus was switched on the pre-assembly of the intake system.

3.5.2. Intake system pre-assembly

The logistics worker at FEM S10 places the intake system and the throttle valve on the conveyor belt and scans the DPM codes to ensure the right combination and sequence. The assembly worker at FEM S20 places the intake system from the conveyor belt in an apparatus and screws the throttle valve with a semi-automatic multi power screwdriver. Then mounts a sensor on the intake system as well as a clip for B58 engines. After finishing these operations the intake system is placed on the second conveyor belt and the operator at FEM 140 mounts the intake system onto the engine.

Figure 66 illustrates the initial situation, while utilizing of the logistics worker approximately 0,5 takt times (0,473 min) and FEM S20 for 75%, a takt balance of 0,236 min. It was not possible to further utilize the pre-assembly operator, and that is why it was decided to do a production preparation process / cardboard simulation according to Section 3.2.4, page 67 in order to improve this configuration.

The first step was to asses and evaluate the initial situation by applying methods like the chalk circle, cf. Section 3.2.2, page 55, and spaghetti diagram, page 56, during the first performance test. The kick off meeting was scheduled right after the performance test with the production specialist, industrial engineer, production and logistics planner, as well as the responsible supervisors of assembly and logistics areas.

The highlights of defining the initial situation in the kick off meeting were the four handling operations of the intake system and the throttle valve, the non-value-added activity of scanning the DPM code of both parts and the enormous walking distances of the logistics worker. After reaching an agreement on the initial situation, existing pre-assemblies of line C in Steyr and line D in Munich, were compared to the situation of line E and premises for the cardboard simulation were defined.

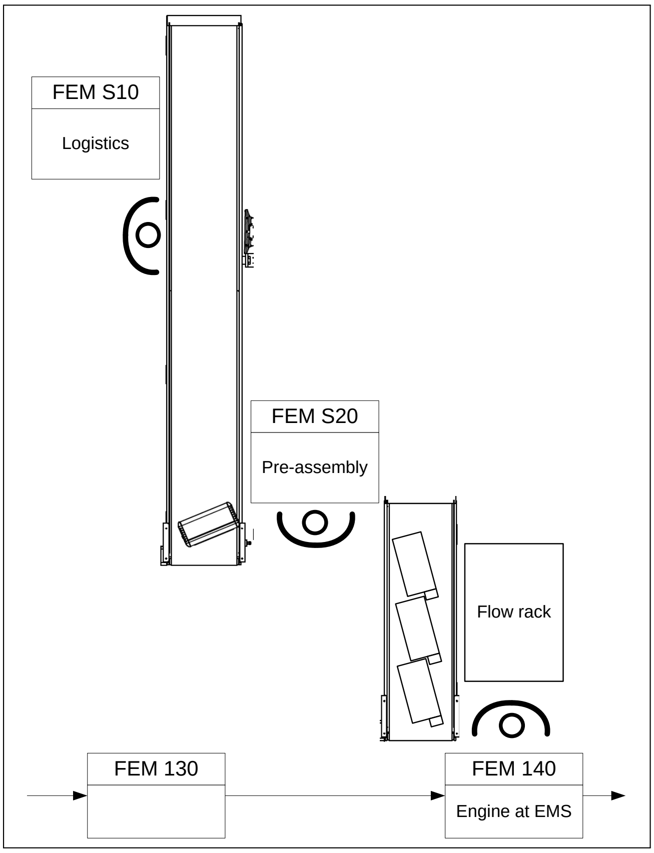


Figure 66.: Intake system pre-assembly - initial situation

The primary goal was to utilize the assembly operator at FEM S20 and to reduce the handling operations. Additional goals include the DPM code scan should either be skipped or automated and an automatic release order for replenishment or use of a simple KANBAN system. An important premise for the simulation was that no trays can be used, as the pre-assemblies in Line C and D did, to avoid additional handling activities.

During the simulation the core team came up with a simple and low-cost idea. The assembly worker picks the intake system from turning racks, and places the pre-assembled part on the existing conveyor belt in a changed layout, illustrated in Figure 67. It is possible to eliminate one handling operation and the empty rack works as a kanban, which is triggering replenishment.

The walking distance of 9 meters per takt for the logistics worker is reduced to 2,4 meters (0,030 min) plus handling of boxes (0,080 min), which utilizes the operator at FEM S20 to 87% (0,819 min). The flow rack for both throttle valves is in the distance range 3, which eliminates the walking distances. Also the scans of the DPM codes performed by logistics is eliminated and to ensure assembly of the right parts, a pick-to-light system can be installed.

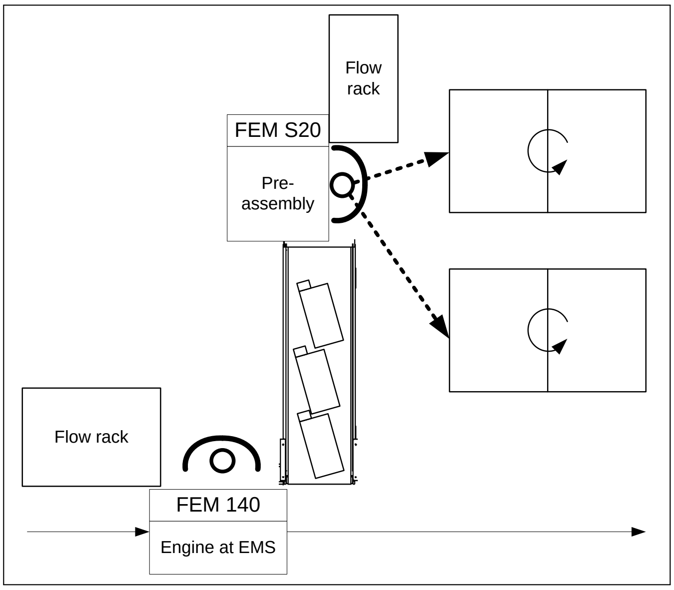


Figure 67.: Intake system pre-assembly - improved layout

This is an example of optimization of the interface between assembly and logistics according to section 3.2.2 and leads to a direct productivity increase of 0,5 operators (0,473 min). This measure also indirectly improves productivity as the 0,110 minutes extra for FEM S20 are performed during the takt balance.

Additionally, the operator at workstation FEM 140 in the initial situation had to turn 180° to reach for part, whereas in the improved layout the flow rack is on the right side, which improves the distance range for getting parts. Also the required space is reduced due to the removal of the long conveyor belt.

The process analysis showed a process time of the semi automatic, multi power screwdriver of approximately 9 seconds (0,150 min) where the operator is not bound. This makes parallel operations possible. The operator can mount the sensor and the clip for B58 during the process time, which results in a reduction of the cycle time by 0,103 minutes.

3.6. End-of-line-test

The end-of-line-test area receives the engine from the final assembly, starting with the elevator TEE 010, illustrated in Figure 68. Two operators set up the engine for a second leak test, one on the intake side (TEM020) and one on the outlet side (TEM030) of the engine. The engine has to passes a second leak test and is then filled with engine oil and fuel, before it runs through a final functional test. This final test checks the engine for correct friction coefficient of the crankshaft lift distribution, leak-tightness and all engine functions including the electrical system.

The three manual workstations 080, 100 and 130 dismantle the test equipment and assemble the last parts, such as various caps and covers, a clutch for manual transmission and prepare the engine as agreed upon with the car assembly factories. The final check of the so-called "dress level" of the engine is performed by a camera, before leaving the assembly line B/G/E.

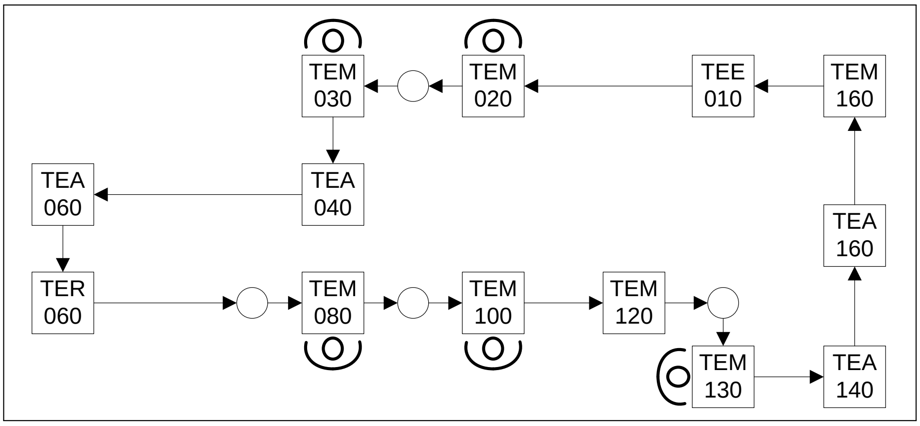


Figure 68.: Layout end-of-line-test

3.6.1. Initial situation

The diagram in Figure 69 shows the initial line balance of the end-of-line-test area. Workstation 020 and 100 have a negative takt balance of up to 0,090 minutes at TEM 100. These two workstations set up and respectively take down the test equipment at the intake side of the engine, which indicates more work content. Workstations TEM 030 and 080 perform operations on the outlet side and are underutilized.

The operator at workstation TEM 130 assembles clutches for manual transmission, which leads to a huge cycle time spread. The target time for assembling a clutch is 0,631 minutes for manual and zero minutes for automatic transmission. Additionally the operator cleans every 3rd workpiece carrier with a vacuum cleaner and wipes every 10th with a towel. The predetermined time for the cleaning operations amount to 0,185 minutes per takt. The diagram in Figure 69 shows the utilization of workstation 130 with a rate of 26% manual transmission.

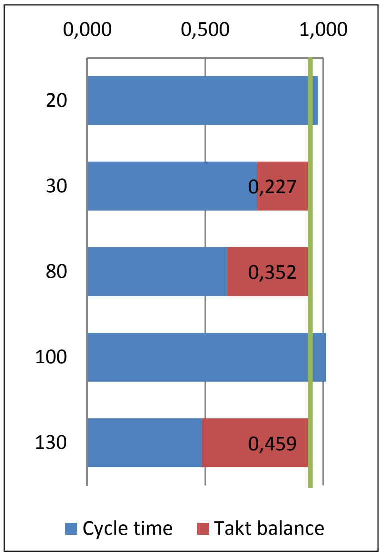


Figure 69.: Line balance - initial situation

Workstations	5	#
Available time	4,727	min
Total cycle time	3,810	min
Total takt balance	0,917	min
Total takt balance	19	%
Potential	1	#

Table 27.: Line balance - summary

Table 27 summarizes the initial line balance of the end-of-line-test. There is a total cycle time of 3,810 minutes with a takt balance of 0,917 min. Keeping the WPC run-in times in mind, which is waiting time, the potential of one operator would be even higher.

3.6.2. Layout change

The sum of total cycle times of TEM 080 and 130 exceed the takt time of 0,945 min. However when shifting between the two workstations, the run-in times can be eliminated. In the initial layout the walking distance of approximately 10 meters, with a target target time of 0,125 min, is too high for combining these two workstations.

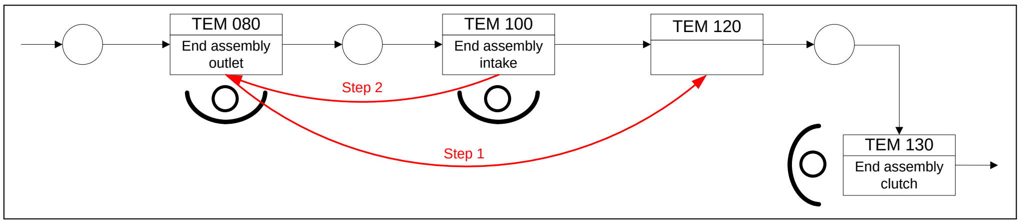


Figure 70.: End assembly workstations - initial layout

The layout of the end-of-line-test illustrates the empty workstation TEM 120 which could be used. Figure 70 shows a detailed layout of the end assembly workstations 080 to 130. Due to the existence of the turning tables, indicated with the white circles between the workstations it is possible to switch workstations and reduce the walking distance to two meters.

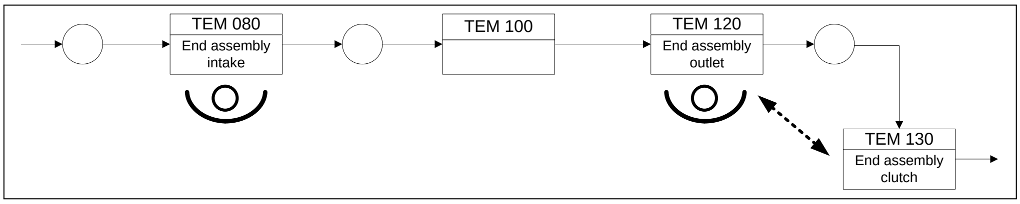


Figure 71.: End assembly workstations - improved layout

The red arrows in Figure 70 show the switch of the workstations. Step 1 is moving the end assembly on the outlet side from TEM 080 to 120; followed by moving the end assembly on the intake side from TEM 100 to 080, step 2. Next is changing the directions of the turning tables of the assembly line in order to have the correct engine positions at the workstations. Lastly is the combination of end assembly on the outlet side with the clutch assembly, illustrated in Figure 71.

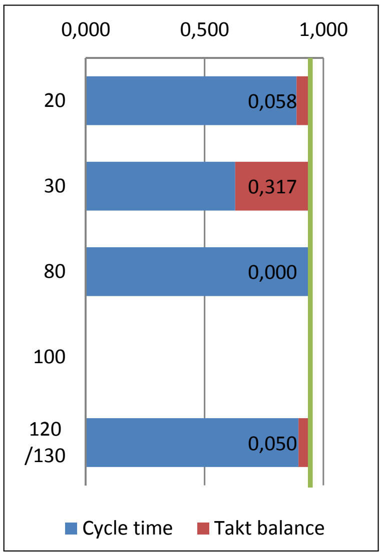


Figure 72.: Line balance - layout change

Workstations	4	#
Available time	3,782	min
Total cycle time	3,356	min
Total takt balance	0,426	min
Total takt balance	11	%
Potential	0,5	#

Table 28.: Line balance - summary

The diagram in Figure 72 shows a takt balance of only 0,050 minutes for workstation 120/130. This however is at a 26% rate of manual transmission. With an increasing amount of clutches to be assembled, the cleaning operations can be completely or partly moved to workstation 030 to avoid over-utilization. Additionally, a utilization of 0,090 minutes of the WPC run-in times, 0,117 min run-in time per workstation, were incorporated for TEM 020, 030 and 080, which is now end assembly inlet side. This eliminates the negative takt time balance of TEM 080. A further possibility to utilize TEM 030 is moving work content from final assembly to workstation 030. However these possibilities were not further investigated in this thesis.

Table 28 shows a direct productivity increase by changing the layout. An indirect increase in productivity is achieved with the utilization or elimination of the run-in times, which equals 0,454 minutes. The takt balance and the potential is decreased to 11% and 0,5 operators respectively.

4. Results

Recommendations for the transition of the defined goal to the productivity roadmaps for the years 2016 and 2017 are offered in this chapter. The goal was to reach a productivity increase of 6% per year, with a focus on the manual workstations of the assembly line. Figure 73 illustrates the annual productivity increase, with an initial processing time of 76,044 minutes per engine and the annual target decrease of 6% for the years 2016 and 2017. The diagram shows a gap of 5,8%, between the initial situation in December 2014 and the target at the end of 2015. The roadmap for 2016 will use the 76,044 minutes of processing time as basis, which is a labor quantity of 76, because the defined concepts and identified potentials may be realized before 2016.

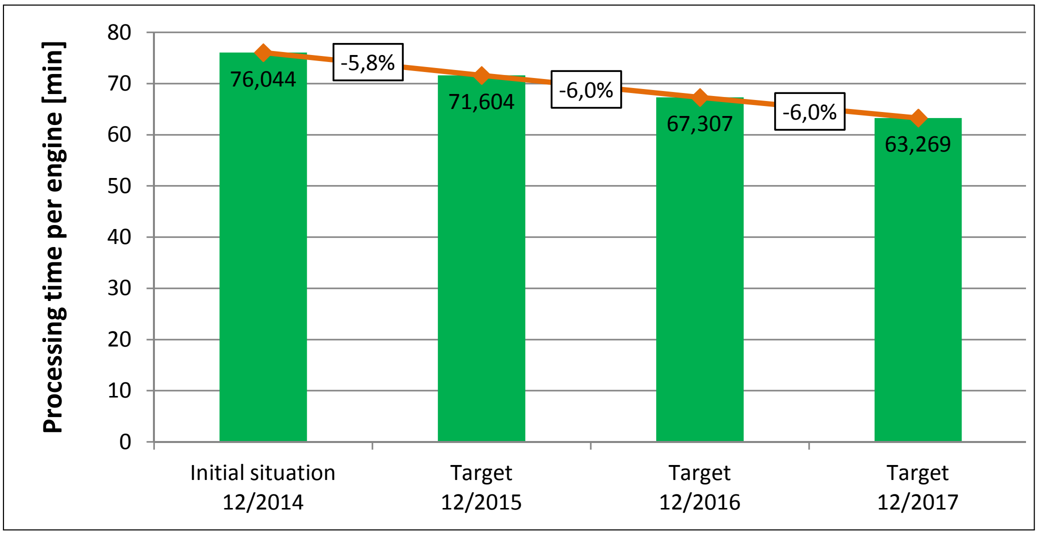


Figure 73.: Target processing time per engine

The potentials and concepts of the investigated areas which include the cylinder head assembly, the engine block assembly, the final assembly and the end-of-line-test in Chapter 3, are allocated to the roadmaps. Complex concepts, with a number of premises, such as the line balance proposal for the engine block assembly in Section 3.4.3, are not entered with the assessed potential in labor quantity. These potentials will be entered in separate positions so as to calculate the correct imputed value, when the measures are realized.

The identified potentials of Section 3.2.2 on page 57, are summarized in Table 29. The potentials are each assigned to a category in the productivity roadmap. The potentials identified with process analyses are listed in category *A) Use of VPS-methods*, and are all in Table 29, except simple automation and automation. Every automation is listed in category *B) Automation*. Expected product improvements which lead to an elimination or decrease of assembly operations are listed in category *C) Product improvement* of the productivity roadmap.

Update existing line balance.
Update process times for power screwdrivers.
Optimize process times for power screwdrivers.
Utilize process times.
Utilize WPC or EMS run-in times.
Avoid tool changes for power screwdrivers.
Avoid workpiece carrier turns.
Optimize workstations.
Optimize interface between assembly and logistics.
Simple automation.
Automation.

Table 29.: Identified potentials

The one shift operation will continue until the end of 2015, the assembly line will then increase to a two shift operation. By the end of 2016, the operation should increase to three shifts. This is especially important for the allocation of the potentials for automation. The defined pay-off period is 3 years and labor costs for one operator is approximately 70.000 Euro. These factors lead to a possible investment of 420.000 Euro for a two shift operation, when reducing one workstation for both shifts.

The factors required for the productivity roadmap are labor quantity, production output and paid attendance time. The production output is defined as 495 engines per shift and the paid attendance time is 498 minutes, which is defined in Table 4. The labor quantity for the roadmap for 2016 is 76 and for 2017 it is defined as 67. The imputed values equal the total values in the roadmaps, because it is not yet possible to estimate the time of realization of the measures.

4.1. Productivity roadmap for 2016

The measures intended for realization in 2016 for the cylinder head is the concept for the implementation of the BMW chaku-chaku mode, described in Section 3.3.3. With a redistribution of work contents and the use of processing times, it is possible to implement the BMW chaku-chaku mode and reduce the number of operators in the manual loop of the cylinder head assembly. The material handling situation must be adopted for the implementation, otherwise the effort and costs are low.

The identified potentials in Table 22 for the line balance proposal of the engine block assembly are entered into the roadmap, due to the complexity. Additional developments resulting from product improvements, such as first tightening operations for two parts and closing caps for parts, are entered in category C. For a realization of the line balance proposal, an additional decrease of 0,6 is entered into the roadmap, to reach a direct productivity increase of 4 operators.

The positions for the roadmap of the final assembly are the identified potentials in Table 26. The 2,237 minutes are entered separately in the categories. The optimization of the interface between assembly and logistics leads to a budget transfer of 0,5 operators from logistics to assembly. A direct productivity increase of the 0,5 operators can be realized in the assembly by integrating the logistics operations and optimizing them with a change of layout, described in Section 3.5.2. The extra handling operations of the pre-assembly worker can be performed during the takt balance, which represents idle time.

A layout change in the end-of-line-test area will lead to a direct increase in productivity. A switch of the end assembly workstations described in Section 3.6.2, makes it possible for one operator to work at two workstations. After every engine, the operator moves to the next workstation which makes it possible to eliminate the WPC run-in times. Additionally, it is possible to utilize run-in times of the remaining workstations in this area by 0,270 min.

Table 30 shows the potentials entered in the roadmap per area with a possible productivity increase of 11,85%. The complete productivity roadmap for 2016 is illustrated in Appendix A.2. This document has been kept in the original German language, because it is required as a working document at BMW Steyr.

Area	**Potential**	**Productivity increase**
Cylinder head assembly	1 #	1,32 %
Engine block assembly	0,6 # and 2,893 min	5,28 %
Final assembly	0,5 # and 2,237 min	3,58 %
End-of-line-test	1 # and 0,270 min	1,67 %
Sum		**11,85 %**

Table 30.: Entries for the productivity roadmap 2016 per area

4.2. Productivity roadmap for 2017

The concepts and potentials for the 2017 productivity roadmap are with first automation. The assembly line is intended to be in three shift operation by then, which decreases the pay-off time and respectively increases to possible investment volume per reduced workstation.

A total investment of 210.000 Euro in the cylinder head assembly by automating workstations ZGM 190 and 201, including a multi power screwdriver, leads to a reduction of one operator in the manual loop. The concept described in Section 3.3.4, uses automation examples based on BMW's reference production system, which are realized in line F in Munich.

The line balance with first automation of the engine block assembly is described and discussed in Section 3.4.4. The automation of the screwing connections of workstation REM 100, including an automatic assembly of the fitting sleeves, would amount to an investment of approximately 500.000 Euro. This would make a reduction of one workstation in group 1 of the engine block assembly possible. The automation of the screwing connections at REM 238, in combination with an automatic DPM code reader, requires investment of 265.000 Euro for a cycle time reduction of 0,324 minutes. However, the possible combination of workstations REM 238 and 265 does not lead to a direct productivity increase, because the work contents have to be moved from REM 265 and would require a workstation in group 2 to be opened up. Screws supplied with washers represent a product improvement for category C and would make a combination of the workstations REM 268 and 287 possible.

After assessing the final assembly with production experts at BMW, a possible productivity increase of one operator was entered into the roadmap for 2017. This should be realized by optimizing the line balance and therefore reducing the takt balance. Furthermore, the idea for optimizing the interface between logistics and assembly for the exhaust turbocharger was entered in the roadmap. Because the concept was not assessed in this thesis, the estimation of the potential of 0,5 operators was not included.

The entries for the productivity roadmap per area are shown in Table 31, with a total productivity increase of 6,36%. The roadmap for 2017, with the incorporated concepts and potentials, is illustrated in Appendix A.3.

Area	**Potential**	**Productivity increase**
Cylinder head assembly	1 #	1,49 %
Engine block assembly	1 # and 1,268 min	3,37 %
Final assembly	1 #	1,49 %
Sum		**6,36 %**

Table 31.: Entries for the productivity roadmap 2017 per area

4.3. Projection of the labor quantity

The targets of an annual productivity increase of 6% in the productivity roadmaps were reached with 11,85% for 2016 and 6,36% for 2017. However, not all potentials from the roadmaps which are realized will lead to a direct productivity increase. This means a transition from cycle time to takt balance is happening and not a decrease of the total processing time. The diagram in Figure 74 illustrates a projection of the total labor quantity of the investigated areas of line G and E.

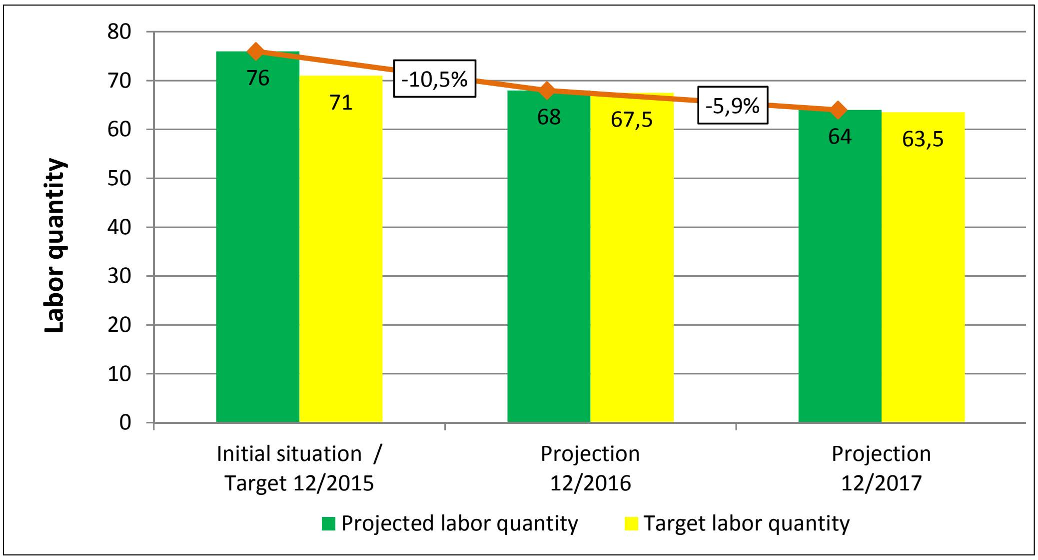


Figure 74.: Projected labor quantity

The green columns represent the initial and the projected labor quantity for 2016 and 2017, by incorporating the concepts with direct productivity increases from Chapter 3. The yellow columns are the (rounded) target labor quantity with an annual decrease of 6%, starting with 71 operators at the end of December 2015. The target labor quantity for December 2016 was increased by 0,5 operators due to the budget transfer of the pre-assembly FEM S20 in the final assembly from logistics and was projected to December 2017.

The diagram shows a 10,5% decrease from the initial situation to the projected situation in December 2016, which is a reduction of labor quantity by 8. A further reduction from 2016 to 2017 by 4 operators leads to a projected labor quantity of 64. By realizing all the productivity increases, there will still be a 0,5 gap between the projected quantity and the target quantity for both December 2016 and December 2017. However, the initial situation does not consider pending budget increases for the processing time. These budget increases would reduce the current gap to the target processing time and therefore positively influence the projection for the labor quantity.

5. Conclusion

The assembly line for four- and six-cylinder petrol in-line engines in the modular kit design was in very early stages of production at the beginning of this thesis. The focus of the mixed model assembly line in pilot production was on the manual workstations and the operators bound to takt. The reduction of non-value-added activities was achieved through process analyses in the cylinder head assembly, the engine block assembly, selected parts of the final assembly and the end-of-line-test. These process analyses in the different areas made it possible to identify potentials to reduce the processing time for assembling the B48 and B58 engines, shown in Table 32.

Update existing line balance.
Update process times for power screwdrivers.
Optimize process times for power screwdrivers.
Utilize process times.
Utilize WPC or EMS run-in times.
Avoid tool changes for power screwdrivers.
Avoid workpiece carrier turns.
Optimize workstations.
Optimize interface between assembly and logistics.
Simple automation.
Automation.

Table 32.: Identified potentials

Creating approaches that create stable work cycles together with lean oriented line balancing principles, were defined and applied to line balancing concepts. Beyond that, innovative solutions to increase productivity were evaluated, these include handheld power screwdriver with an automatic screw feed system and a screw feeder with a soap dispenser mechanism.

The processing time per engine is a key figure in BMW's engine production network and is in direct relation to the labor quantity and the production output. The defined concepts and potentials were incorporated in a productivity roadmap to reach the goal of a 6% annual productivity increase. The measures defined for the roadmap of 2016 make a total productivity increase of 11,85% possible. For the roadmap in 2017, automation possibilities were used to reach 6,36% of total productivity increase. The productivity roadmaps are illustrated in Appendix A.2 and A.3.

The concepts and potentials presented in this thesis should lead to direct productivity increases in order to meet the target labor quantity. Table 33 shows the direct productivity increases, as illustrated in Figure 74, when realizing the measures described in Chapter 3. It is possible to reduce one operator in the cylinder head assembly by implementing the BMW chaku-chaku loop, where two operators switch to the next free workstation upstream. The concept for 2017 includes the full-automation of the semi-automatic workstations, which results in a direct productivity increase. The line balance proposal for 2016 in the engine block assembly shows the potential to close four workstations and two more by automation in 2017.

With the identified potentials in the final assembly, it is possible to reduce the number of operators bound to takt by two. Additionally, the optimization of the interface between assembly and logistics for the intake system pre-assembly, will lead to another direct productivity increase with a budget transfer of a labor quantity of 0,5. By 2017, an optimization of the line balance should make it possible to reduce one more operator. The proposed layout change in the end-of-line-test makes it possible for one operator to work on two workstations. However by realizing all the defined measures, the gap between the initial situation and the target is too high and the direct productivity increases will not be sufficient to reach the target labor quantity.

Area	**2016**	**2017**
Cylinder head assembly	1 #	1 #
Engine block assembly	4 #	2 #
Final assembly	2 + 0,5 #	1 #
End-of-line-test	1 #	-
Sum	**8 + 0,5 #**	**4 #**

Table 33.: Direct productivity increase per area (in labor quantity)

The start for implementing the concepts in assembly line B/G/E is the actualization of the current line balance with all operations and workstations. In order to establish a solid foundation for the optimization, it is suggested to implement a standard work description for operations at the workstations. This will increase transparency and form a foundation that is important for optimization and continuous improvement. At the same time, these standard work descriptions should serve as support for instructing operators.

The assembly line B/G/E is based on a reference system, which makes the findings applicable for the existing lines in Steyr, Munich and Hams-Hall, as well as similar engine assembly lines. The identified potentials and principles for line balancing are of particular interest, as they are independent of the work contents performed.

This thesis combined the skills, duties and responsibilities of production specialists and industrial engineers as defined by BMW. It is clear from the results, that knowledge in predetermined time systems, standard data, waste analysis and line balancing is a favorable combination of competences for increasing productivity in assembly lines.

6. Outlook

This thesis mainly focused on the manual workstations and the operators bound to takt and therefore did not include further factors for possible improvement. Potentials regarding the structure personnel of the engine block assembly and the final assembly were not incorporated. Section 3.1.6 describes the group size of 10 operators per foreman. With a reduction of 24 operators to 20 in the line balance proposal it would be possible to also reduce one operator in the structure personnel. The same is true for the final assembly; there are currently 3 foremen for 23 operators. By reducing the operators to 20, as suggested in the roadmap for 2017, it would be possible to reduce one foreman.

This thesis used a constant product mix of 60% B48 and 40% B58 engines. The forecast for the years 2017 and further, favors an increase of B58 engines, which increases productivity at some workstations and the budget. Also the possibilities in moving parts or operations between the areas of the assembly line have to be assessed and defined. This must be under consideration of the automatic stations, especially the test benches, in between the areas.

After reaching serial operation, an increase in the production output would be reasonable and should be further investigated. An increase of 25 engines per shift would lead to a takt time reduction of 0,045 minutes per workstation, hence to a direct productivity increase of approximately 5%. For realizing an increase of production output, all areas of assembly line B/G/E must increase production, in order to guarantee the same pace and synchronization.

The combination of all these factors will make it possible to reach the goal of 6% annual productivity increase in labor quantity. Furthermore, a technical revision of the B48 and B58 engines is planned for 2017/2018 and therefore, an integration of new engine variants in assembly line B/G/E. This will lead to significant changes in the layout and a new start for an assessment of potentials.

A. Appendix

A.1. BMW standard data sheet

Working with Screws / Bolts

Screws/Bolts		Code	Distance range 1	2	3	No. Code	
Pick up screw/bolt, place in position, screw in 2 rounds	screw/bolt with or without fixed washer	M-SAK E	60	85	100	140	x
		M-SAK Z	100	125	140	141	x
	screw/bolt with washer	M-SAUX	100	125	140	142	x
	screw/bolt and washer and additional washer or similar	M-SAZX	130	180	210	143	x
Pick up screw/bolt, place in position without screwing in	screw/bolt with or without fixed washer	M-SBK E	35	60	75	144	x
		M-SBK Z	60	85	100	145	x
	screw/bolt with washer	M-SBUX	75	100	115	146	x
	screw/bolt and washer and additional washer or similar	M-SBZX	105	155	185	147	x
Handful	handful of screws/bolts incl. discarding remainder	S-AGHR	50	85	105	16	x
	from handful place one part in 2 rounds	M-SPKE	50	60	65	148	x
	from handful place one part without screwing in	S-PBE	20	30	35	27	x
E = 1 part / Z = 2 parts							

Handling Auxiliary Materials/Tools			Code	Distance range 1	2	3	No. Code	
Pick up tool, place in position, set down	counter holding tool		M-SFV E	50	70	85	150	x
			M-SFV Z	30	40	45	151	x
	multi-auto-screwdriver		M-SFA E	80	100	115	152	x
			M-SFA Z	60	70	75	153	x
	manual auto screwdriver, drill screwdriver, ratchet, open-end wrench, slip-on wrench, screwdriver	without screw	M-SFB E	50	70	85	154	x
			M-SFB Z	30	40	45	155	x
		with screw	M-SFC E	55	85	110	156	x
			M-SFC Z	40	60	70	157	x
Tightening with torque	measuring range: 0 - < 30 Nm		M-SDA E	80	100	115	158	x
			M-SDA Z	60	70	75	159	x
	measuring range: > 30 - < 500 Nm		M-SDB E	90	110	125	160	x
			M-SDB Z	70	80	85	161	x
E = first position / Z = additional position								
Changing bit on tool			M-SWW X	90	120	150	162	x

Screwing parts in by hand		Code	≤M10	>M10 ≤M20	(self-) tapping screw	No. Code	
DIN -screws, nuts or self-tapping screws screw-in: 1 mm	using one or two hands	M-SEHX	15	10		170	x
	socket wrench	M-SESX	20		15	171	x
	drill-screwdriver	M-SEDX	10		5	172	x
	ratchet	M-SERX	25	20		173	x
	open-end wrench	M-SEGX	80	60		174	x

BMW - Standard Data

Master Data

Issue 2007-3	
Time Unit	
TMU	Min.
1	0,0006

Get and Place

Weight	Condition	Parts	Fit	Code	Distance range 1	2	3	No. Code	
≤ 1 kg ≤ 2.2 lb	easy	1 part or simult.	aprox.	S-AAE	20	35	50	1	x
			loose	S-ABE	30	45	60	2	x
			tight	S-ACE	40	55	70	3	x
		2 parts.	aprox.	S-AAZ	20	35	50	4	x
			loose	S-ABZ	50	65	80	5	x
			tight	S-ACZ	70	85	100	6	x
	difficult	1 part	aprox.	S-ADE	20	45	60	7	x
			loose	S-AEE	30	55	70	8	x
			tight	S-AFE	40	65	80	9	x
		2 parts	aprox.	S-ADZ	40	65	80	10	x
			loose	S-AEZ	60	85	100	11	x
			tight	S-AFZ	80	105	120	12	x
		simult.	loose	S-AES	50	75	90	13	x
			tight	S-AFS	60	85	100	14	x
	handful		aprox.	S-AGH	40	65	80	15	x
	handful, throw remainder back		aprox.	S-AGHR	50	85	105	16	x
> 1 kg to ≤ 8 kg > 2.2 lbs to ≤ 17.6 lb		1 part	aprox.	S-AHE	25	45	55	17	x
			loose	S-AJE	40	65	75	18	x
			tight	S-AKE	50	75	85	19	x
		2 parts	aprox.	S-AHZ	50	70	80	20	x
			loose	S-AJZ	80	105	115	21	x
			tight	S-AKZ	100	125	135	22	x
> 8 kg to ≤ 22 kg > 17.6 lbs to ≤ 48.5 lb		1 part	aprox.	S-ALE	80	105	115	23	x
			loose	S-AME	95	120	130	24	x
			tight	S-ANE	120	145	160	25	x

Place

Parts	Fit	Code	Distance range 1	2	3	No. Code	
1 part	aprox.	S-PAE	10	20	25	26	x
	loose	S-PBE	20	30	35	27	x
	tight	S-PCE	30	40	45	28	x
2 parts	aprox.	S-PAZ	10	20	25	29	x
	loose	S-PBZ	40	50	55	30	x
	tight	S-PCZ	60	70	75	31	x

Motion Cycles

	Code	Distance range 1	2	3	No. Code	
One motion	S-ZAX	5	15	20	32	x
Motion sequence	S-ZBX	10	30	40	33	x
Reposition and one motion	S-ZCX	30	45	55	34	x
Pressure Application > 10 N	S-ZDXX	20			35	0

Operate

		Code	Distance range 1	2	3	No. Code	
Operating elements	simple operate	S-BEE	10	25	40	36	x
	compound operate	S-BZE	30	45	60	37	x

Body Motions

		Code	TMU	No. Code	
Walk 1 m / 39.4 in, Turn body > 90° 1 step (stairs)	in assembly process	S-KAM	25	38	0
	get parts for car	S-KAV		39	0
	car body to car body	S-KAK		40	0
Bend, Stoop, Kneed (incl. Arise)		S-KB	60	41	0
Sit and Stand		S-KC	110	42	0

Visual Control

	Code	Distance range 1 2 3	No. Code	
Yes / No decision	S-VKXX	15	43	0

Read

			Code	Distance range 1	2	3	No. Code	
3 digits 3 letters or 1 word	handling card	first	S-LME	50	75	95	44	x
		further	S-LMWX	15			45	0
	without card		S-LOXX	15			46	0

Handle Tool

			Code	Distance range 1	2	3	No. Code	
1 tool	aprox.	first activity	S-HEUE	35	55	75	47	x
		additional activity	S-HEUZ	20	30	35	48	x
	loose	first activity	S-HELE	50	70	85	49	x
		additional activity	S-HELZ	30	40	45	50	x
	tight	first activity	S-HEEE	60	80	95	51	x
		additional activity	S-HEEZ	40	50	55	52	x
2 tools	aprox.	first activity	S-HZUE	50	70	90	53	x
		additional activity	S-HZUZ	30	40	45	54	x
	loose	first activity	S-HZLE	80	100	115	55	x
		additional activity	S-HZLZ	50	60	65	56	x
	tight	first activity	S-HZEE	95	115	130	57	x
		additional activity	S-HZEZ	65	75	80	58	x
1 or 2 tools	further activity		S-HWAXX	10			59	0

Process

		Code		No. Code	
Standard time required TTU (processing time)	worker bound to process	S-PTG	1	90	0
	worker unbound to process	S-PTU		91	0
	movement of vehicles / workpiece carrier	S-PTF		92	0

A.2. Productivity roadmap 2016

Zeit/Einheit bei ZM-4. Roadmap für die Erreichung der Zielsetzung von 1% Produktivitätssteigerung/Monat. **28.03.2015**

Montage Benzinmotoren B48B/B58 Band G/E (ZM-48)

	Maßnahme/Thema	2015	Jan	Feb	Mrz	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Dez	Produktivität: - anw. Personal (in PL/Tag)	Produktivität: + Stückzahl/ Sch.(in E.)	Produktivitäts-steigerung [Gesamtwert] in %	Produktivitäts-steigerung [kal. Jahreswert] in %
A	**Einsatz von WPS-Methoden**														**-8,1** PL		**10,67%**	**10,67%**
ZK	Optimierung Arbeitsvorgänge und Implementierung BMW Chaku-Chaku		◆												-1 PL		1,32%	1,32%
RM	Aktualisierung Abtaktung / Arbeitsplan		◆												-0,76 PL		1,00%	1,00%
RM	Belegung von WT-Einlaufzeiten		◆												-1,59 PL		2,09%	2,09%
RM	REM 345/350: Verschraubung Aggregateräger zusammenlegen		◆												-0,15 PL		0,19%	0,19%
RM	REM 130: Ablage DMC Gerät auf TSD Montagevorrichtung		◆												-0,22 PL		0,29%	0,29%
RM	Optimierung Arbeitsplätze und Abtaktung		◆												-0,6 PL		0,79%	0,79%
FM	Anpassung Schrauberprozesszeiten (zum Großteil umgesetzt)		◆												-0,78 PL		1,02%	1,02%
FM	FEM S20: Übernahme Logistikumfänge + Layoutumstellung		◆												-0,5 PL		0,66%	0,66%
FM	Belegung von WT-Einlaufzeiten		◆												-0,93 PL		1,22%	1,22%
FM	Aktualisierung Abtaktung / Arbeitsplan		◆												-0,33 PL		0,43%	0,43%
PT	Layoutänderung Abrüstplätze - Zusammenlegung Auslassseite und Kupplung		◆												-1 PL		1,32%	1,32%
PT	Belegung von WT-Einlaufzeiten		◆												-0,27 PL		0,35%	0,35%
															0,00 PL		0,00%	0,00%
B	**Automatisierungen**														**-0,30** PL		**0,39%**	**0,39%**
RM	REM 520: Einsatz eines Schraubers mit automatischer Schraubenzuführung Befestigung KS-HD-Leitung		◆												-0,05 PL		0,07%	0,07%
RM	Teileabrufe automatisieren		◆												-0,08 PL		0,11%	0,11%
FM	FEM A10: Automatisierte WT-Friegabe durch Laser und Tassenhandling		◆												-0,02 PL		0,03%	0,03%
FM	Teileabrufe automatisieren		◆												-0,14 PL		0,19%	0,19%
															PL		0,00%	0,00%
C	**Produktverbesserung**														**-0,6** PL		**0,78%**	**0,78%**
RM	REM 390: Entfall Anheften ZKH B58		◆												-0,22 PL		0,29%	0,29%
RM	REM 415: Entfall Verschlusskappen für Rail		◆												-0,17 PL		0,22%	0,22%
RM	REM 430: Enftall Schrauben an Rail anheften (anderer Schraubenlieferant)		◆												-0,18 PL		0,23%	0,23%
RM	Syntak B48: Reduzierung Montagezeit durch besseres Handling		◆												PL		0,00%	0,00%
FM	FEM 140: Anheften Sauganlage; andere Schraube, Möglichkeit für Akkuschrauber		◆												-0,03 PL		0,04%	0,04%
															PL		0,00%	0,00%
D	**Umtaktung**														**0,0** PL		**0,00%**	**0,00%**
																	0,00%	0,00%
																	0,00%	0,00%
E	**Gegenläufige Effekte (Zusätzliche Tätigkeiten ohne Mehrbudgetierung)**														**0,0** PL		**0,00%**	**0,00%**
																	0,00%	0,00%
																	0,00%	0,00%
Summe															**-9,0** PL		**11,85%**	**11,85%**

Legende:
- ◆ (grün) ... Grüner Meilenstein: Ab hier ist Maßnahme wirksam
- ◆ (gelb) ... Gelber Meilenstein: Ab hier wird Maßnahme voraussichtlich wirksan
- ◆ (rot) ... Roter Meilenstein: Umsetzung der Maßnahme fraglicl
- ◆▭ ... Maßnahme mit begrenzter Wirksamkei

A 3

A.3. Productivity roadmap 2017

Zeit/Einheit bei ZM-4. Roadmap für die Erreichung der Zielsetzung von 1% Produktivitätssteigerung/Monat. **29.03.2015**

Montage Benzinmotoren B48B/B58 Band G/E (ZM-48)

	Maßnahme/Thema	2016	Jan 2017	Feb	Mrz	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Dez	Produktivität: - anw. Personal (in PL/Tag)	Produktivität: + Stückzahl/ Sch.(in E.)	Produktivitäts-steigerung [Gesamtwert] in %	Produktivitäts-steigerung [kal. Jahreswert] in %
A	**Einsatz von WPS-Methoden**														**-2,0** PL		**2,99%**	**2,99%**
RM	Zusammenlegung REM 268/287 in Kombination mit Lösung für REM 268 (siehe Produkterbesserung)														-1 PL		1,49%	1,49%
FM	Optimierung Arbeitsplätze und Abtaktung - Reduzierung Taktausgleich														-1 PL		1,49%	1,49%
FM	ATL Vormontage: Auflegen von ATL durch Montage (~0,5 PL)														PL		0,00%	0,00%
															PL		0,00%	0,00%
															PL		0,00%	0,00%
															PL		0,00%	0,00%
B	**Automatisierungen**														**-2,26** PL		**3,37%**	**3,37%**
ZK	Konzept - Automatisierung ZGM 190; 201 und Einsatz Doppelschrauber														-1,00 PL		1,49%	1,49%
RM	Automatisierung steuerseitige Verschraubungen (REM 100)														-0,76 PL		1,13%	1,13%
RM	Automatisierung Passhülsen einschlagen (oder Verlagerung nach SB)														-0,18 PL		0,27%	0,27%
RM	Automatisierung TÖNS Muttern incl. Automatische DMC Lesung														-0,32 PL		0,48%	0,48%
															PL		0,00%	0,00%
C	**Produktverbesserung**														**0,0** PL		**0,00%**	**0,00%**
RM	REM 268: Zylinderkopfschrauben mit verliersicheren Muttern (oder automatisierte Lösung) (-0,567min)														PL		0,00%	0,00%
															PL		0,00%	0,00%
															PL		0,00%	0,00%
															PL		0,00%	0,00%
															PL		0,00%	0,00%
															PL		0,00%	0,00%
D	**Umtaktung**														**0,0** PL		**0,00%**	**0,00%**
																	0,00%	0,00%
																	0,00%	0,00%
E	**Gegenläufige Effekte (Zusätzliche Tätigkeiten ohne Mehrbudgetierung)**														**0,0** PL		**0,00%**	**0,00%**
																	0,00%	0,00%
																	0,00%	0,00%
Summe															**-4,3** PL		**6,36%**	**6,36%**

Legende:
- ◆ … Grüner Meilenstein: Ab hier ist Maßnahme wirksam
- ◆ … Gelber Meilenstein: Ab hier wird Maßnahme voraussichtlich wirksan
- ◆ … Roter Meilenstein: Umsetzung der Maßnahme fraglicl
- ◆▭ … Maßnahme mit begrenzter Wirksamkei

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