Ognjen Radisic, BSc

Process Stabilisation during Pre-Series Ramp-Up in Low-Volume Production Systems

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Supervisor

Dipl. Ing. Martin Kremsmayr

Institute of Innovation and Industrial Management
Univ.-Prof. Dipl.-Ing. Dr.techn. Christian Ramsauer

Dipl. Ing. (FH) Karl Deutschmann

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In Cooperation with:

Rolls Royce Motorcars Limited

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The accompanying thesis is subject to secrecy. It is not allowed to pass this thesis or parts of it on to third parties without explicit approval of Rolls-Royce Motor Cars Limited

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Preface

Over a century ago, manufacturing vehicles was close to art. Producing one by one, early pioneers were dedicated to their product and customers, and built every single car by hand. Soon after the early mass manufacturing years of the Ford Model T, the number of new variants and derivatives started increasing. Many companies followed this trend, but Rolls Royce stood out as the perfectionist, keeping the art alive. A background in automotive engineering and production, and the determination that there must always be an ideal solution, sparked an interest in analysing the complex and uncertain phase of ramp-up. However, without the support of certain people, this endeavour would have never been possible, and I would like to thank all of them for supporting me along the way.

Firstly, I would like to express my gratitude towards Univ.-Prof. Dipl.-Ing. Dr.techn. Christian Ramsauer, for enabling this thesis at his institute and agreeing to the special terms and conditions. Your effort and commitment in lectures and especially in the research for this thesis have remained a stable source of motivation. To my supervisor at the university, Dipl. Ing. Martin Kremsmayr, thank you for supporting the thesis with all the peculiar circumstances associated with it, and taking the risk when accepting a thesis written abroad. Thank you for the guidance and input during the six months.

I would also like to thank my practical supervisors at Rolls Royce. Thank you Karl for the invaluable input and discussions that helped ignite the fever to research this topic and provide the necessary infrastructure. Thank you Ian, for supporting the thesis and adopting me into your team, although never planned. Special thanks goes to Dalibor, without you, this thesis would never exist, and my appreciation for your effort will never cease.

I am grateful for having worked and shared a flat with you Katharina, our discussions have fuelled both our academic research and personal life, and although we had our moments of disagreement, we both pulled through. Thanks to my colleagues Caro, Filip and Toby, for your support towards the end of this thesis. Never would I have been able to accomplish it in the way I did without your help.

Finally, a big thank you goes to my family. Thank you mum, dad, Stella, Bako, Djidjo and my girlfriend Elisabeth, who never lost hope in me actually finishing my studies. Thank you for supporting me all the way, although it might have seemed desperate sometimes. Elisabeth, thank you for your support all this time while we were separated. I would have never achieved the targets set, if it were not for your continuous backing and understanding. Hvala za sve.

Ognjen Radisic

Abstract

Since decreasing the time to full production capacity increases the return on investment remarkably, the transitioning phase from product development to series production, also known as ramp-up, receives more and more attention. Staying in plan with quality and costs confronts companies and management with high complexity and instability as product variety increases. Processes designed for series production need to be tested, however especially low volume production is limited by low numbers and a lack in process knowledge. Due to limited data availability, taking decisions and steering production to a final stage is challenging for every process partner.

The present thesis examines the theoretical background of production processes, process stability and production ramp-up, and combines it with observations performed at a British high luxury car manufacturer. The observations made led to the formalisation of seven demands to be fulfilled in order to achieve a stable ramp-up. An extensive state of the art review revealed that demands towards anticipative planning and fast response to disturbances were not answered. Targeting these defined requirements, a newly developed methodology proposes a solution on how to stabilise the production during ramp-up.

Following a base approach of gathering data, deriving information and thus building knowledge, the methodology is split into three parts. Firstly, a general overview is generated using data analysis. This provides management with a pro-active field of action, and gives the opportunity to identify and deal with the biggest risks. During the build, a proposed real time monitoring system offers an overview of occurring problems and delivers potential temporary and long-term solutions.

This methodology was then applied to the ramp-up of a high luxury low volume producer in order to validate the process. By introducing the theoretical considerations into a practical field and observing its outcome, the drawn conclusion confirmed the practicability and benefit of the methodology.

Kurzfassung

Durch die höhere Frequenz mit der neue Produkte eingeführt werden, bekommt die Produkteinführungsphase, auch bekannt als Anlauf, zusätzliche Bedeutung. Der wirtschaftliche Erfolg des Produktes hängt direkt von der zur Erreichung der Kammlinie benötigten Zeit ab. Im Zieldreieck von Zeit, Kosten und Qualität und der zusätzlichen Erhöhung der Produktvielfalt, erleben Unternehmen und Management eine Periode hoher Instabilität und Komplexität. Serienprozesse müssen erprobt werden und speziell die niedrigen Volumina der Kleinserienfertigung erschweren den Aufbau von Prozesswissen. Mit nur wenigen Daten ist das Fällen von Entscheidungen und das Steuern der Produktion weitaus anspruchsvoller für sämtliche Prozesspartner.

Die vorliegende Arbeit untersucht den theoretischen Hintergrund von Produktionsprozessen, Prozessstabilität und Produktionsanlauf, und kombiniert diesen mit Erfahrungen aus empirischer Datenerhebung bei einem britischen Luxusautomobilhersteller. Die Synthese der Informationen führte zur Erarbeitung von sieben Anforderungen, die allesamt von einer Methodik erfüllt werden müssen, um einen stabilen Anlauf zu gewährleisten. Schlussfolgernd aus einer ausführlichen Untersuchung von wissenschaftlichen Arbeiten wurde festgestellt, dass eine antizipative Planung und zeitgerechtes Feedback in der Vergangenheit nicht ausreichend in Lösungsvorschlägen inkludiert wurden. Die Erfüllung dieser beiden Anforderungen, zusätzlich zu den schon bestehenden, war Ziel der Entwicklung einer Methodik zur Stabilisierung der Produktion während der Anlaufphase.

Aufbauend auf einer allgemeinen Vorgangsweise bestehend aus Datengewinnung, Informationsableitung und daraus folgendem Wissensaufbau, ist die Methodik ebenfalls aufgeteilt in drei Teile. Anfangs wird basierend auf den Zielen durch statistische Methoden ein Grunddatengerüst erarbeitet. Durch Identifizierung der größten Risiken wird dem Management ein proaktives Betätigungsfeld geboten. Während der Bauphase ermöglicht eine auf Zeitnahmen basierende Überwachung in Echtzeit die exakte Analyse von Systemstörungen und liefert dadurch in weiterer Folge den Grundstein zur Lösungsfindung.

Die entwickelte Methodik wurde während des Anlaufes bei dem besagten Luxusautomobilhersteller validiert. Durch die Einführung und Anwendung der theoretischen Überlegungen in einem industriellen Umfeld wurde der Mehrwert als auch die Ausführbarkeit der Methodik bestätigt.

Table of Contents

I. List of Abbreviations

AP	Anlaufproduktion, production scale-up phase at BMW
BBG	Bestaetigungsbaugruppe, first prototypes built at BMW
BMW	Bayrische Motoren Werke Aktien Gesellschaft
DC	Delivery Concept
FMEA	Failure Mode and Effects Analysis
KPI	Key Performance Indicator
MLS	South main line at RRMC
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OLS	One Line System
PDCA	Plan-Do-Check-Act method
PQM	Product Quality Management
QM	Quality Management
RRMC	Rolls Royce Motorcars Ltd.
RRNM	Rolls Royce New Model Architecture
RTM	Real Time Management
SOP	Start of Production
SPC	Statistical Process Control
TPM	Total Productive Maintenance
upd	units per day
VS0	Vorserie 0, first pre-series phase at BMW
VS1	Vorserie 1, second pre-series phase at BMW
VS2	Vorserie 2, third pre-series phase at BMW
WS	Workstation

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1 Introduction

1.1 Initial Situation

When automotive manufacturing started its first production over a century ago, each product was hand-built, and the expenses for a single car were too high for common people. By offering the Model T in one single variant, Henry Ford was able to reduce the costs of production for each individual car[1]. Over the years, the principles of economies of scale became more popular, the trend was to produce more and more. Increases in production volumes required robust processes, so that the amount of sales would match the production output. Ford pursued this perfectionism, but in 1922, the eternal rival General Motors already took over the lead in sales, and one of the many contributing reasons was the fact that they had more than one option.

With the saturation of global markets and increasing competition between multinational actors, companies try to distinguish themselves to avoid being “stuck in the middle”. Some chose the cost leadership, where production volumes continuously increased while others tried to improve their quality and thus having a non-monetary edge towards competitors[2]. The third group of manufacturers went down an alternative path, producing niche products for a specific customer base, but as globalisation of markets increased, new competitors came to the field and stirred up old production schemes. Nowadays, companies try to fulfil the needs of every single customer group and niche market to increase their profit.

Catchwords such as Internet of Things, Industry 4.0, Mass Customization and Lot Size 1, were added to companies goals additional to those of lean management. In order to become these agile production systems, a company needs fast ramp-ups, possibility of quick changes in production layout and the ability to deal with last minute engineering changes. As a result, associated processes are affected. With the introduction of new competitors and technologies to the market, the diversification diffused even to entirely integrate different powertrain systems. Consequently, companies find themselves in a peculiar spot. In order to increase sales volume, manufacturers aggressively open new niche markets and produce ever-smaller lot sizes, but with each new variant and technology, production complexity is increasing[3]. On the other hand, well-established companies based their success around perfecting processes to a point, where high repeatability guaranteed economic success.

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[1] Fisher, Ittner 1999, p. 771

[2] Porter 1999, p. 70ff.

[3] Fisher, Ittner 1999, p. 772ff.

The defined key performance indicators for process stability and maturity rely on a high amount of statistical production data. Agile systems tend to stay below the threshold of statistical relevance, resulting in difficulties to confirm the process fitness[4].

With an increase of product portfolio in one factory, new products hold a threat to interrupting existing assembly lines. With little data available, predicting potential risks poses a difficult challenge[5]. Every ramp-up of a new product can lead to unstable processes, directly influencing the output and profit of current production lines. Therefore, for estimations regarding maturity, process capability and potential irritations early indicators need to be introduced, and once products are launched, the system needs stabilising and control.

1.2 Research Focus and Scope

Discrete manufacturing companies and process industries producing consumer goods are facing similar challenges. Today's customer driven markets demand for a high degree of customisation, while still being affordable, resulting in constant changes in production layout and process steps.

With the introduction of new competitors from different fields, especially the electronics industry, car manufacturers have to handle a high pressure on their markets. By diversifying and introducing new technologies to their products, Original Equipment Manufacturers (OEM) try to cover all future possibilities. This results in the complexity of the product increasing with each added part. Further fuelled by an increase of manufacturing technologies, entire businesses fail due to change implementation not managed well.

The Japanese car manufacturers had an early understanding of how process stability and production output links to costs and quality. By introducing lean methods like Kanban and Total Productive Maintenance, amongst others, they managed to limit production risks in their facilities, ensuring consistent assembly. Not soon after, their suppliers and European car manufacturers would follow adapting their methods. Production was stabilised with only a margin of tolerance, where managing global supply chains down to the smallest minute has become common.

One of the remaining sources of instability in these networks is the introduction of new products, whether it is to an existing production line or in a new facility. The production ramp-up is often very unstable, but performance in early phases directly affects the future success of a product. Hence, by smoothing the ramp-up curve, reducing inconsistencies in time and quality, the saved costs ensure the economic success of the entire project.

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[4] Wiendahl 2002, p. 650

[5] Wiendahl 2002, p. 652ff.

As traditional high volume car manufacturers base their success on a higher diversification, adaptability of the entire systems needs to improve. Due to the lack of experience, one's focus turns to those producers that have faced the problems of customer orientation from the beginning: Highly customised low volume production systems.

1.3 Practical Need and Research Goal

Research in the field of ramp-up has often focused on issues that are more general. SCHUH'S[6] and BRUNS'[7] research analysed general management strategies on how to handle the ramp-up, without giving clear instructions on the actions that need to be taken. Others like GARTZEN[8] investigated the complexity of the phase, suggesting methods for controlling instabilities, but their practicability is not simple. These limitations become even clearer once the target production system shifts from a mass production system to low volume production. Applying concepts such as target volumes or first time yields to systems where one product is the outcome of an entire day is unreasonable. Another limiting factor is the headcount. Measuring and capturing data often needs huge administrative support, which is normally limited in the ramp-up phase.

This thesis is set to develop a methodology to stabilise the ramp-up production in a low volume context. To do so, three research questions have to be answered:

1) How can the production and ramp-up be stabilised?
2) How to measure process capability in a low volume production and logistics environment?
3) What key performance indicators are needed for effective production control?

1.4 Structure and Approach

This thesis serves as the base for discussion on these questions, as well as being the documentation for the research performed to answer them. Having defined science as either being formal sciences or natural sciences[9], this work at hand falls under the category of applied sciences, a sub category of the natural sciences.

In consequence, practical consideration is the base of the research. Following the approach of ULRICH[10], shown in Figure 1-1, the result of this thesis is the synthesis of observed behaviour and review of theoretical information.

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[6] Schuh et al. 2008
[7] Bruns 2010
[8] Gartzen 2012
[9] Ulrich et al. 1984, p. 169ff.
[10] Ulrich et al. 1984, p. 193

Chapter 1 is providing a base overview on the topics discussed, as well as an introduction onto the research goal and focus, followed up by a definition of basic principles and terminology of processes, stability and ramp-up in Chapter 2. General characteristics of assembly and logistics systems are discussed before introducing the topics of quality and process control. The challenges and differences of low volume manufacturing systems, especially in the field of automotive engineering are highlighted in the last two sub-chapters.

The third chapter acts as a synopsis of current approaches, and shows an extensive elaboration on existing solutions, their benefits and shortcomings. A description of the research gap concludes the assessment of these current approaches based on the principle discussion.

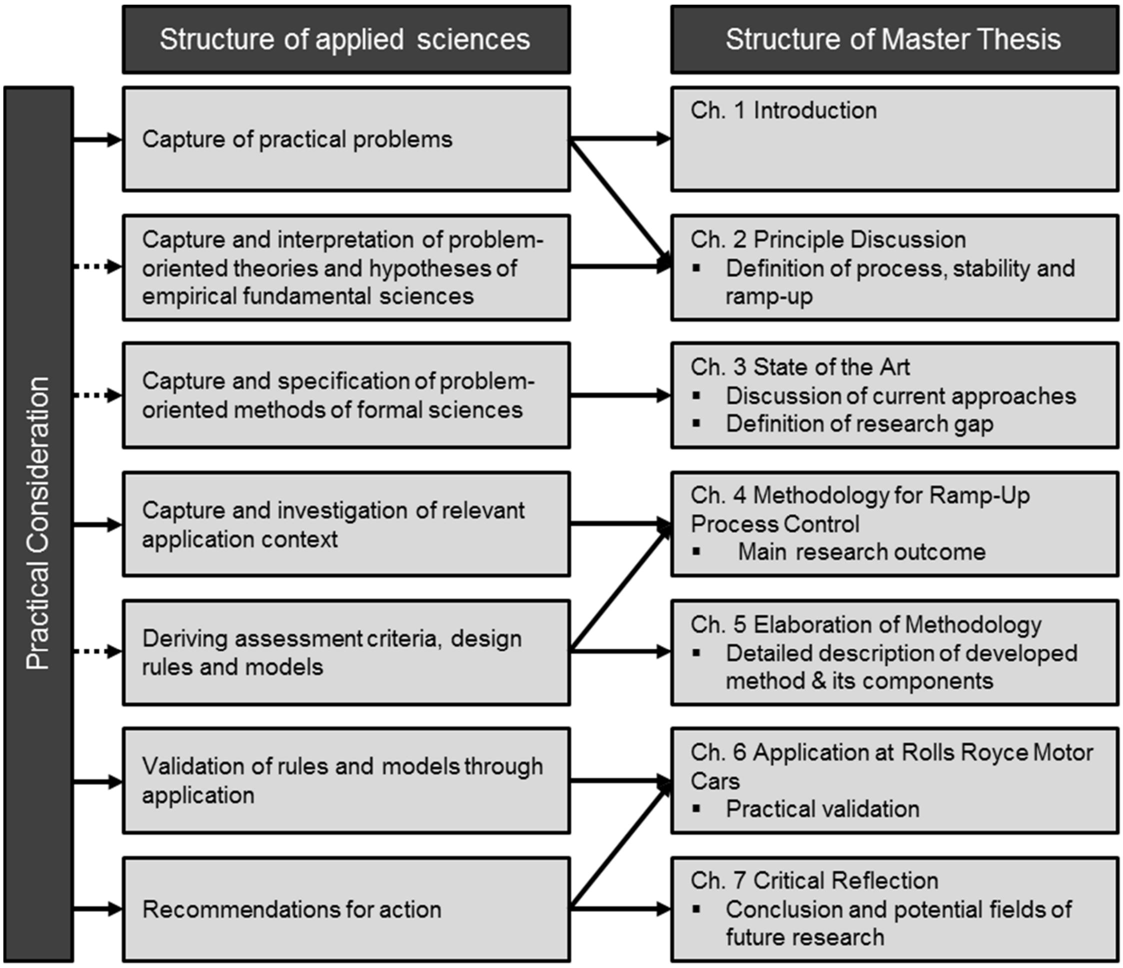

Figure 1-1 Structure of thesis based on ULRICH[11]

Chapter 4 describes the outcome of the research, formulated by the underlying research hypotheses and the methodology, followed by an extensive elaboration of the methodology in Chapter 5. Chapter 6 validates the practicability and assumptions of the

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[11] Based on: Ulrich et al. 1984, p. 193

methodology, by means of analysing results from empirical research performed at Rolls-Royce Motor Cars Ltd.

Chapter 7 finalises the thesis with a critical reflection, and discusses the potential for future research fields.

2 Basic Definitions

To understand the context of the problem comprehensively, an overview of the generic terminology of production systems, production control, as well as implications during ramp-up in low-volume assembly is necessary.

The initial Chapter 2.1 provides a base understanding of production systems, establishing the distinction between assembly and logistics, and their interaction. Chapter 2.2 introduces the concept of management based on processes and determines basic parameters and processes for their respective systems. Building on the premises of Quality Management (QM), Chapter 2.3 elaborates on the terminologies of quality, capability and stability, concluding in statistical process control as a means of achieving process targets. Chapter 2.4 investigates on methods of production management, offering basic information on control loops, data gathering by means of key performance indicators, and finalising with cross-functional impacts of disturbances.

The fifth chapter, Chapter 2.5, introduces a phase that every product has to undergo from development to series production, the ramp-up. A portrayal of factors influencing the outcome of ramp-up follows up on a base definition and establishes it as an unstable system. Chapter 2.6 is dedicated to the discussion of low-volume manufacturing systems. The last Chapter 2.7 is then finalising the gathered information and linking it to the specifics of automotive companies.

2.1 Production Systems

Manufacturing companies are, as further discussed in Chapter 2.6, processing input and transforming it to an output. To ease the clarification of associated processes, a closer look on manufacturing systems in general is necessary. Therefore, observing a production system exposes different areas inside, as seen in Figure 2-1.

The factory is the core transformation process of a company. A steering entity, usually the management or process leader, sets a target value for the execution entity. By going into further detail, one observes single assembly stations, again with their specific input and output parameters. The final division of theses sub-organisations has the worker and his work steps as the smallest entity.[12]

As production systems are complex entities themselves, the more complex the product, the higher the demand towards clear process definitions and responsibilities for logistics and production[13]. For easier understanding, the general term “Production System” defines a system with discrete manufacturing steps, leaving out the process industry. After an exhibition on the general term system in Chapter 2.1.1, Chapter 2.1.2 illustrates

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[12] Dyckhoff 2000, p. 5

[13] Wangenheim 1998, p. 14

the borders of assembly and logistics, followed up by an analysis of these systems in Chapter 2.1.3 and 2.1.4.

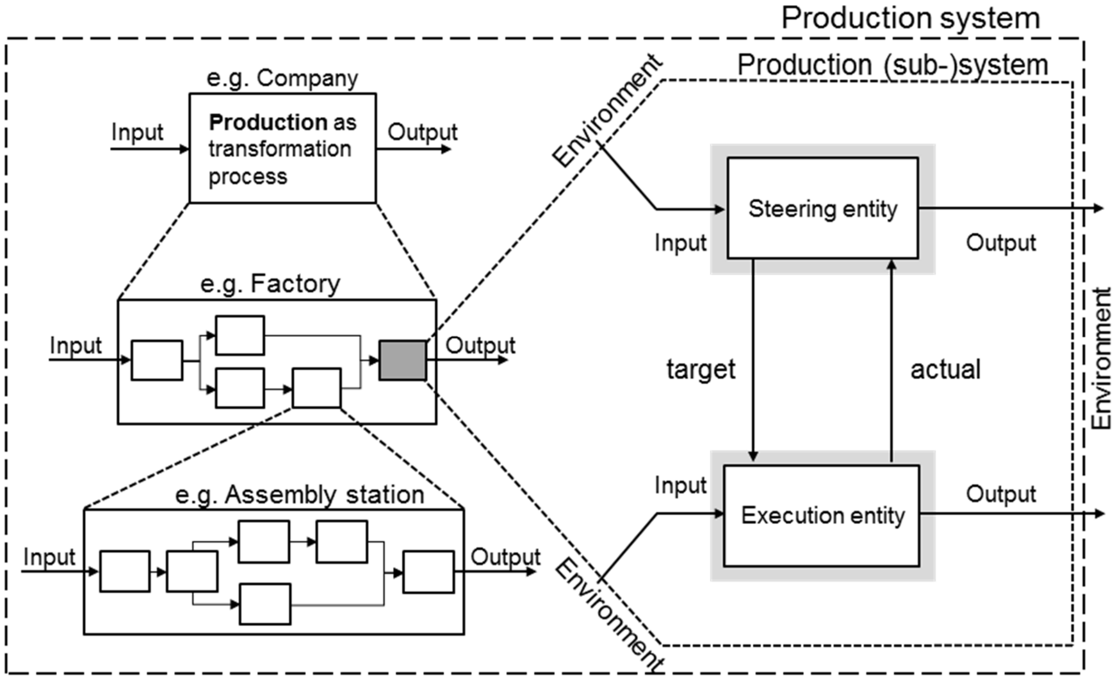

Figure 2-1 Elements of a production system[14]

2.1.1 Definition of System

To discuss the term systems, basic terminology needs to be clarified which is then valid for this thesis. The general composition of a system shown in Figure 2-2 presents the three basic components element, relation and system border. Elements are entities in the system, connected through their relation to each other. A relation is any kind of interaction between these elements. The system border is posing the boundaries to other systems, e.g. the responsibilities of a department.[15]

Closed off systems are rare, and most others have a certain relation to their environment or other systems. Characteristically, internal relations of a system are stronger than external ones[16]. System elements can be anything, from single individuals up to entire departments, which then again form a system, a subsystem. Specifications to the types of relationships apply to different systems depending on their purpose with their own set of challenges.

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[14] Translated from German: Schuh 2014, p. 3

[15] Haberfellner, Daenzer 1997, p. 4

[16] Haberfellner, Daenzer 1997, p. 5

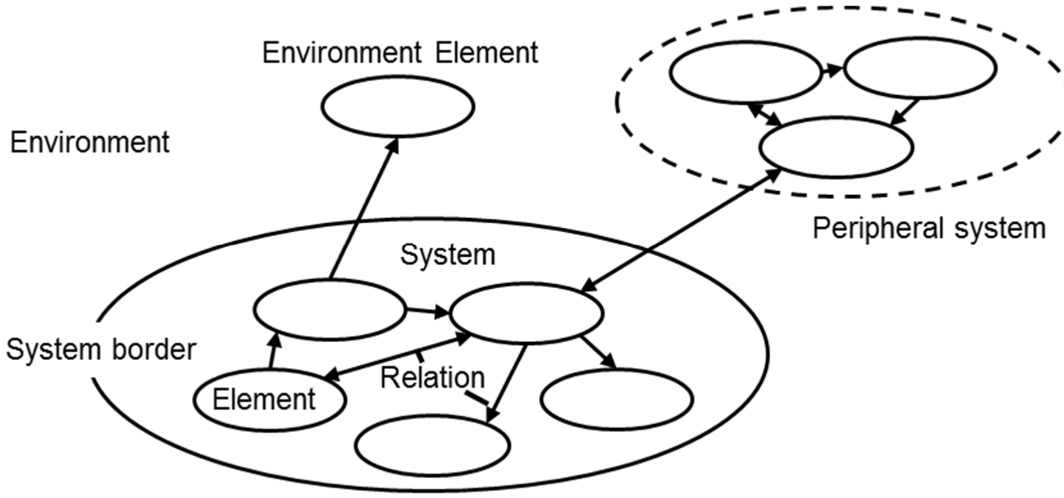

Figure 2-2 Basic terms of the system approach according to HABERFELLNER[17]

2.1.2 Demarcation of Logistics and Production

In order to determine the implications and cross effects of an unstable process on a production system, the terms assembly and logistics require clarification. Outside the plant, the borders are clear. Logistics is anything transporting the product while anything that transforms the object is production. The system "Factory", as shown in Figure 2-1, consists, amongst others, of the two sub-systems "Logistics" and "Production". In there, the boundaries are between departments[18]. BAUDIN simplifies the demarcation by using the example of an assembly line. The movement of products between various stations in line is treated as production time as the assembly executes it, while logistics delivers the input goods to the line. Therefore, a hypothetical system border is around an assembly system, with logistics providing input and transporting the output[19].

2.1.3 Assembly Systems

Assembly is a sub-category of production. While production includes manufacturing or machining, assembly systems only fit together pre-produced parts. No chipping process occurs on assembly lines[20] as these production steps can lead to defects and damage, in the worst-case cause a line stoppage.

Putting and fitting together different parts to sub-assemblies or even finished products characterises the generic system of an assembly plant[21]. By transforming incoming

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[17] Translated from German: Haberfellner, Daenzer 1997, p. 5
[18] Baudin 2004, p. 10
[19] Baudin 2002, p. 10ff.
[20] Baudin 2002, p. 4
[21] Baudin 2002, p. 1

goods, the assembly system satisfies customer-demand. Although not a core task of an assembly plant, quality control is in the highest interest[22].

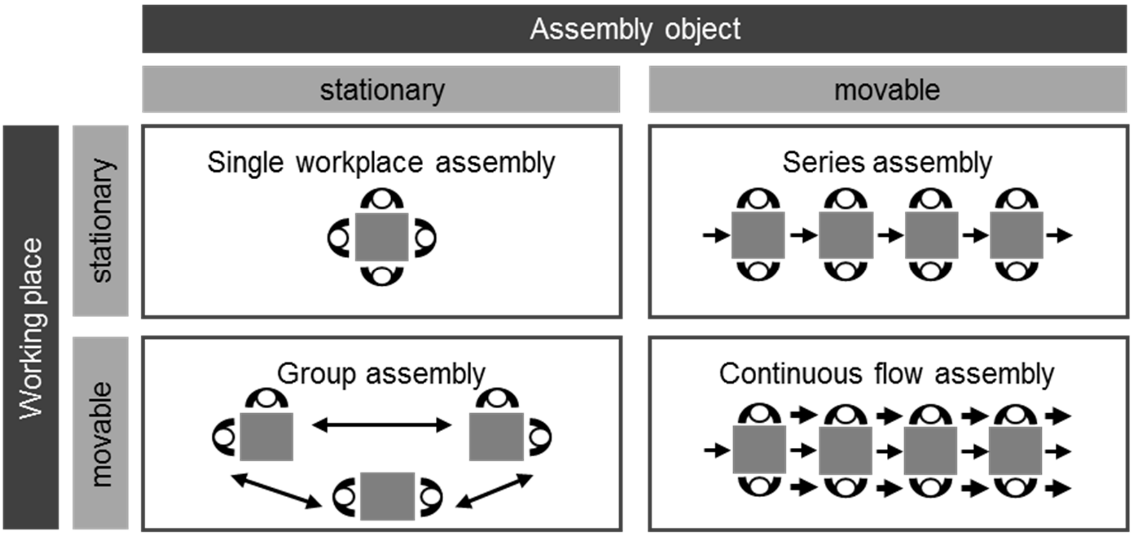

Figure 2-3 Variants of assembly layouts[23]

As seen in Figure 2-3, assembly systems can have various layouts depending on the needs of the product and production volume. Single workplace assembly describes a stationary system, where all workers perform their work task simultaneously. Group assembly is more common in low volume productions, especially in systems that have various low complexity products as an output. When both, the workers and the assembly object moves, the assembly is in a state of continuous flow, for instance in airplane manufacturing. The last group is the series assembly, also known as the assembly line.

In an assembly line, associates perform repetitive tasks while the product moves on a conveyor or hypothetical line. Usually the output does not vary too much in its specifications. The amount products on one line vary in their components is an indicator on the complexity of the product and high differences can lead to instability[24]. Systems performing assembly tasks have to manage their goals towards quality, time and costs. Production management summarises the steering, planning and monitoring of the company's resources to achieve this goal. The term production management will be thoroughly discussed in Chapter 2.4.

Two key figures of an assembly line are the throughput time and takt time, both play an essential role when debating the capabilities and abilities of processes in an assembly system[25].

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[22] Günther, Tempelmeier 2014, p. 6
[23] Based on: Gottschalk 2006, p. 10
[24] Baudin 2002, p. 16
[25] Gottschalk 2006, p. 11

2.1.4 Logistic Systems

As established in Chapter 2.1.2, the organisational scope of logistics is the provision of material to the line, and the processes of distribution after the line. The objective of logistics is to provide the right products with the right quantity and quality at the right time to the right place at the right costs, also known as the 6-R Rule of logistics[26].

Logistics itself is a term that emerged in the industry after 1950. Before, logistics was a phrase used to refer to the military movement of troops, with the base word "logis" referring to the French word for troop housing[27]. Literature refers to the start of modern logistics within the Napoleonic era, as supply to and from the battlefield was a key success factor for victory[28].

Today's industry grants a process oriented logistic system more attention, as effective supply chain management (SCM) is essential for a company's economic situation (see Chapter 2.2.3). PFOHL defines three base flows of goods in logistic systems[29]:

- Direct Material Flow (1-step system)
- Indirect Material Flow (multi step system)
- Direct and indirect material Flow (combinatory system)

A 1-step system describes a direct connection between the source and the consumer, while in a multi-step system an intermediate point exists for collecting and distributing goods.

Various layouts and forms of logistics concepts find application throughout the industries, each with their own advantages and disadvantages. Figure 2-4 portrays some examples from the automotive industry. The centralised layout concepts have a centre hub, where goods are moved towards or away from, with a centre area for communication. The lower left sketch displays a comb concept, where a central area connects the workshop areas similar to a comb. The right bottom picture depicts a single island concept, usually a type seen at old factories, which have grown over the years, without a general concept. While over the years the influence of production on factory layout has diminished, the role of logistics is ever increasing as high production rates in combination with lean stock demand for a high frequency of incoming goods[30].

As a second distintictive criteria towards a logistics system, kitting an line-side supply are two ways of providing material to the line. While the first one puts all parts needed for a specific station into a defined kit prior to the delivery to the station, line-side supply

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[26] Dickmann 2007, p. 27
[27] Arnold et al. 2008, p. 3
[28] Schuh 2013, p. 2
[29] Pfohl 2010, p. 6
[30] Klug 2010, p. 4ff.

has a direct storage and provision at the point of need. In reality a combination of both types can be observed and is the better strategy.[31]

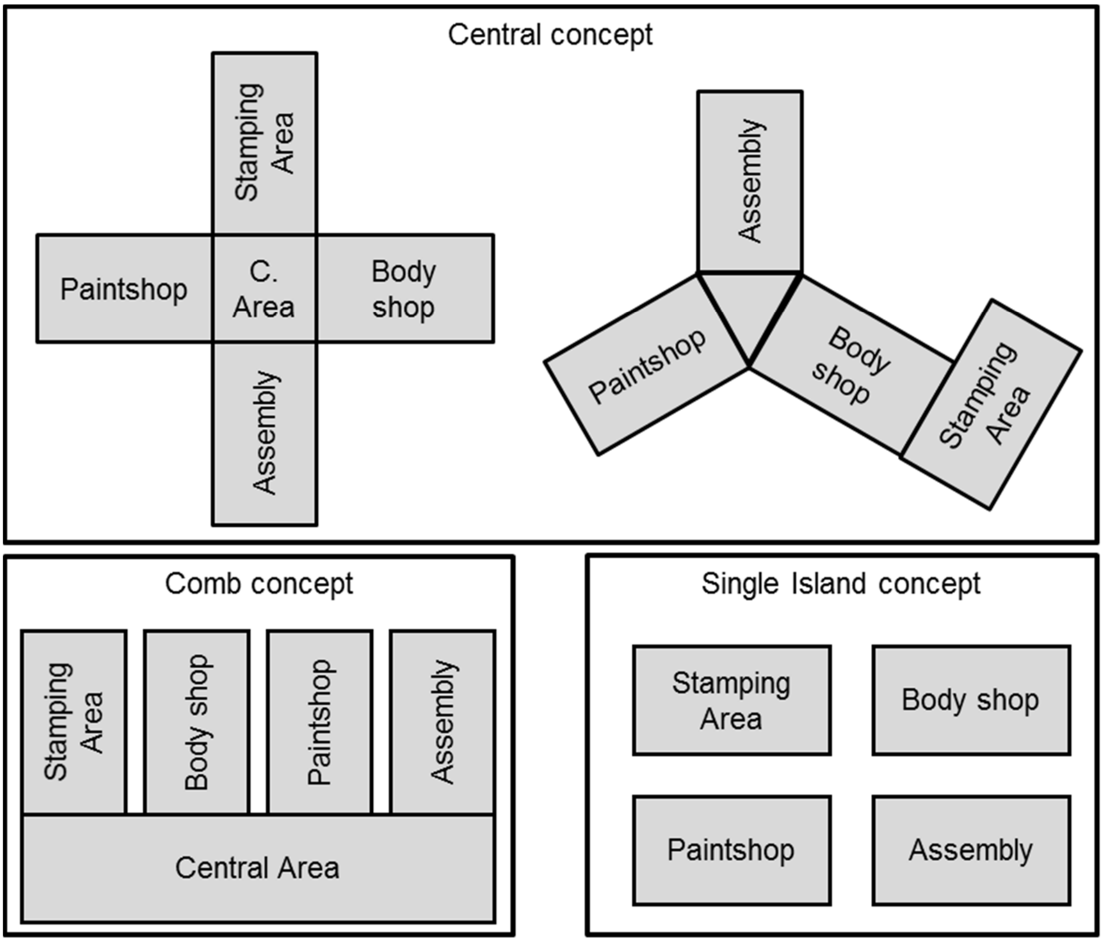

Figure 2-4 Example of different factory layouts in the automotive industry[32]

As both, ARNOLD and BAUDIN describe, the effects of a logistic system onto the production and vice versa, cannot be decoupled, and as such, one has to improve both to satisfy the needs of the enterprise.

2.2 Process Management

After the introduction of system theory, this chapter focuses on processes and process parameters in general, as well as onto those specific to assembly and logistics. Chapter 2.2.1 discusses the general term at hand. Following the elaboration of assembly and logistics systems in previous Chapters, 2.2.2 and 2.2.3 include an analysis of the process parameters for their respective components.

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[31] Baudin 2004, p. 14

[32] Translated from German: Klug 2010, p. 4

2.2.1 Definition of Process

Literature delivers no universally applicable definition of a process. ZOLLONDZ[33] and KOCH[34] provide the definition as a series of activities, actions and tasks for the generation of a product, with a direct relationship to each other, consisting of a measureable input, a measureable value addition (transformation) and a measureable output, as shown in Figure 2-5.

Figure 2-5 Basic structure of a process

Eight core characteristics of a process where identified by MANGLER[35]:

- The entirety of a process has a goal
- It has a defined starting and ending point, and is closed in itself
- In such an entity, a transformation is happening from an input to an output object
- The transformation is a chain of actions and activities in a set period of time
- Generally value is added by the process
- The starting point has a trigger and the result has a receiver
- In a work process the task supporter and material are linked
- To conduct activities and actions, both need information and knowledge

Since the nature of manufacturing in itself fulfils all criteria described above, process orientation started in production systems as early as the production itself. Nevertheless, it was not until the 1980s with the introduction of a process management based approach[36] that basic constructs of process-oriented organisations formed[37].

The orientation from a functional based view on organisations was not satisfying. The reason being that departmental boundaries increased inefficiency by hindering the flow of product development and production. The Introduction of process-oriented organisations as an overlay over the existing departments created a process oriented organisation matrix[38], improving customer order flow in the entire business.

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[33] Zollondz 2011, p. 249
[34] Koch 2012, p. 27
[35] Mangler 2000, p. 194
[36] Striening 1988, p. 48ff.
[37] Zollondz 2011, p. 243
[38] Koch 2012, p. 26ff.

Transformed onto production systems, the process can be further split into a main process, the actual transformation of incoming materials, and several support processes. These support processes include the logistics' ones transportation & delivery, handling, storage, and production maintenance.[39]

2.2.2 Assembly Processes

As established in Chapter 2.1.3, assembly systems have various principles and layouts. Since the processes themselves also differ, a limitation is necessary for this thesis. Throughout this work, assembly systems refers to series assembly, following a flow principle of production.

The assembly process is a sub process of the production process, and thus one of the main parts of the transformation process of a manufacturing factory. It consists of a chain of stations, where every station in itself is a sub-process of the assembly process. It gets its input from the upstream station and additional parts from logistics, and outputs a product to the next station. Multiple sub-assemblies can also be fitted beforehand, some even on their own mini-production lines[40].

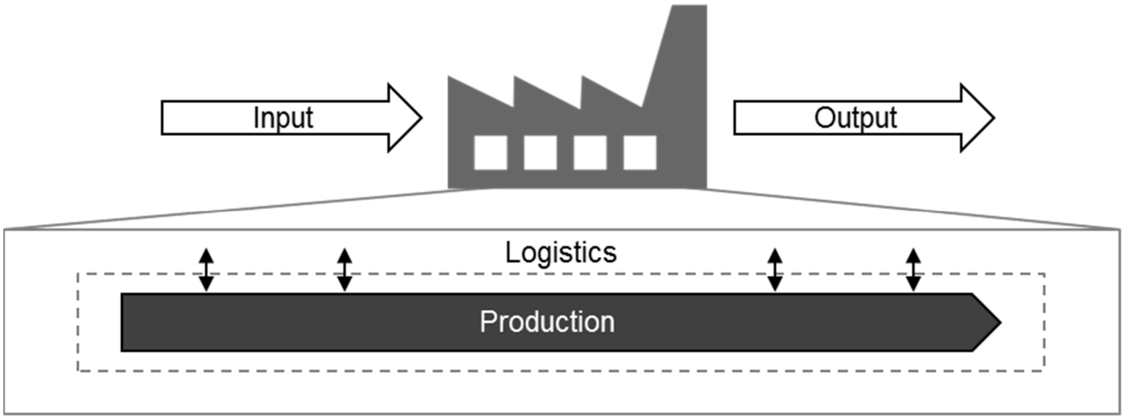

Figure 2-6 Interdependence of logistics and production in a factory

Two parameters of an assembly process need highlighting: Takt time and Throughput time:[41]

$$Takt\ time = \frac{Net\ available\ Production\ Time}{Demand} \qquad \text{Equation 2-1}$$

$$Throughput\ time = \frac{Demand}{Net\ available\ Production\ Time} \qquad \text{Equation 2-2}$$

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[39] Zäpfel 2001, p. 2
[40] Hahn 1999, p. 580
[41] Baudin 2002, p. 42

By comparing the equations, it is obvious that they are the inverse of one another[42]. By synchronising the material flow of all assembly stations, an optimal solution to the production process is given[43].

Takt time is the time it takes to process one product in one station. In balanced systems, takt times do not vary by a lot from one process step to another, as this would lead to waiting queues in front of bottlenecks.

Throughput times on the other hand describe the time it takes a product from the first to the last process step, in effect being the time a product spends on the line.

2.2.3 Logistics Processes

After giving a general definition of processes in Chapter 2.2.1 and the analysis of assembly processes in 2.2.2, this chapter discusses the three base processes of a logistics system, transportation, storage and order processing[44].

Order Processing

Central aspect of every enterprise, the trigger for this process is receiving an order from a customer. As a support process, the flow of information interlinks with the material flow. Every other process of the logistics area is relying on the information gathered, as it includes delivery dates, customer numbers, ordered items, etc.

Transferred onto the production system, the assembly line becomes the customer, demanding goods at a certain position.

Transportation

Transport is the movement of goods from one point to another[45]. Literature differentiates the transportation process by means of internal or external processes. External transport summarises all modes of transport, ranging from truck delivery to airfreight outside of a facility. Internal logistics on the other hand are delivering goods and material to the consumer in the company.

Goals of internal logistics are optimisation of usage (low costs, high capacity usage), high level of service (short transport times and fast delivery) high flexibility and transparency (current situation and key performance indicators)[46].

Storage

Storing goods has various reasons, sometimes in order to use economy of scale effects, sometimes for balancing demand and offer, and enables the specialisation of plants.

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[42] Baudin 2002, p. 58
[43] Hahn 1999, p. 580
[44] Koch 2012, p. 29
[45] Koch 2012, p. 66
[46] Ehrmann 2012, p. 217

Various storage systems exist, but are not relevant for this thesis. Nevertheless, the process is always the same. A mode of transport triggers a goods receiving process, followed by a storage process as an internal logistics process, packaged for use and moved to outgoing goods once needed, where it is picked up for further transport.[47]

Thus, an overall logistics process consists of elements according to Figure 2-7[48]. Key performance indicators used in this thesis are parts availability and missing point of fit (absolute value).

$$Parts\ availability = \frac{\#\ Available\ Parts}{\#\ Total\ Parts} \qquad \text{Equation 2-3}$$

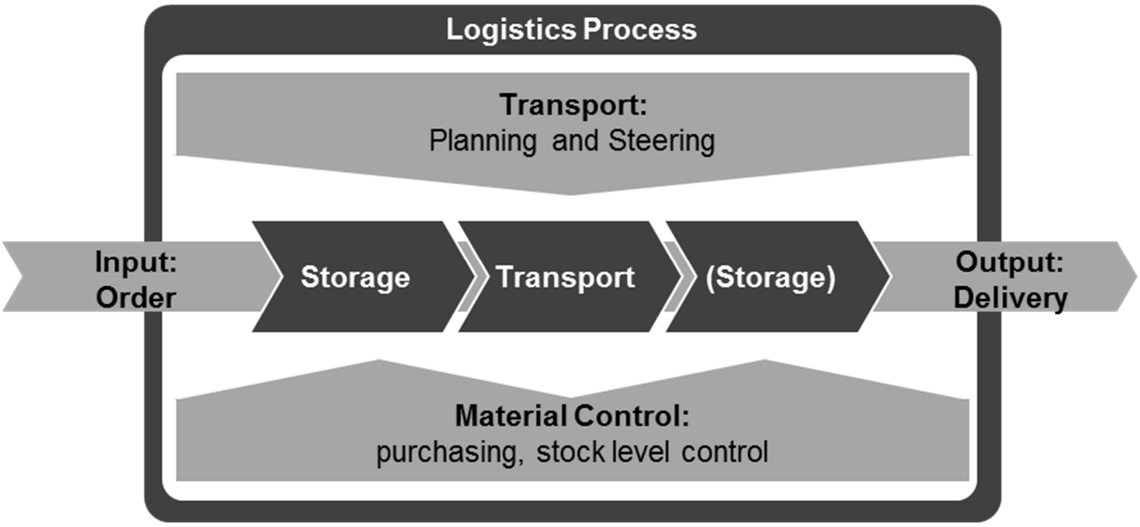

Figure 2-7 Basic logistics process flow based on KOCH[49]

2.3 Process Maturity

In order to determine whether a process has reached the maturity and hence quality and process capability targets, the approach of key performance indicators (KPI) is widely used. During a ramp up phase, different KPI can be collected, all of them dealing with their respective restrictions. Nonetheless, every KPI calls for an evaluation against a certain criterion, whether it is a time based, cost based or quality based. Chapters 2.3.1 to 2.3.3 provide definitions of the terms quality, capability, statistics, and stability. In Chapter 2.3.5 an overview on statistical process control is given.

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[47] Koch 2012, p. 35ff

[48] Koch 2012, p. 29ff.

[49] Based on: Koch 2012, p. 32

2.3.1 Definition of Quality

Mostly associated with positive effects, quality has become a global objective of companies and an important factor for market success and competitiveness. Wording such as quality of life, quality of food and others, are clear indicators that a positive image is associated with the term[50].

In Latin, the word quality was the counterpart for quantity. The first one describing the characteristics of an object, while the latter was the amount of objects[51]. Following first explorations by philosophers in ancient Greece, France and Germany, the term was not common in industries regularly, and no prevailing definition existed until 1972[52] [53].

The ISO 9000:2005 standard defines quality as "degree to which a set of inherent characteristics fulfils requirements"[54]. This is a rather weak definition, as it describes the term quality by means of advertisement, making it possible to add adjectives like poor, good or excellent[55]. Nevertheless, literature agrees in clarifying that quality is not absolute. It is a relative index and one cannot measure it directly[56].

German literature[57] [58] defines quality following the DIN 53350-11 standard as the "Degree of realised properties of an entity against demanded requirements". This definition follows the older ISO definition, and is clearer in showing resulting implications. For better understanding and further clarifications, this is the definition used throughout this thesis. An entity is by this definition anything individually observable or describable[59].

As outlined in this chapter, quality is a relative index, describing the degree of realisation of properties against a pre-defined demand. As a result, to measure the maturity of a product and its quality, targets need to be set and measurement principles need to be established.

2.3.2 Definition of Capability

In order to comprehend the term capability, understanding the term quality is necessary[60]. While quality deals with a single entity, capability deals with a pair of entities. One being a producing entity, the second being the product produced. As with quality, capability has several definitions as well, but no common worldwide standard[61].

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[50] Brüggemann, Bremer 2012, p. 3
[51] Zollondz 2011, p. 163
[52] Geiger, Kotte 2008, p. 67
[53] Zollondz 2011, p. 48ff.
[54] ISO 9000:2005
[55] Geiger, Kotte 2008, p. 71
[56] Brüggemann, Bremer 2012, p. 4
[57] Brüggemann, Bremer 2012, p. 3
[58] Geiger, Kotte 2008, p. 67
[59] Geiger, Kotte 2008, p. 69
[60] Geiger, Kotte 2008, p. 78
[61] Geiger, Kotte 2008, p. 78

GEIGER provides a clear definition of capability being the “ability of an organization, system or process to realize a product that will fulfil the requirements for that product.” An attached for a comment on “statistical process capability” refers to a statistical definition of process capability in terms of process stability, which will be discussed in Chapter 2.3.5. For this thesis, the valid definition is the one given by GEIGER:

Capability is the ability of an entity to realize a product with the demanded requirements (quality). It can apply to a system, process or machine.

Having a capable process on its own is not enough to ensure that the product will adhere to the demands always. Additionally, the repeated output of production needs to be in the respective tolerances.

2.3.3 Definition of Stability

In Mechanical Engineering, stability represents the knowledge of the future state of an object by knowledge of the input variables[62]. Some fields like system theory and control systems define stability as the ability of a system, to rebalance itself after a disturbance[63].

Quality management defines stability with a statistical approach, as keeping the mean value of characteristics controlled[64]. The terms stable and controlled are treated synonymously and as such, a stable process can be described as “a process in a state of statistical control”[65].

Stability is a state of statistical control. The characteristics (of a product or process) are either not changing by a lot, or changing according to expectation[66].

2.3.4 Basics Terms of Statistics

Observing a single value usually does not provide information on the state of the big picture. Gathering data and setting it into context of everything is the goal of the mathematical field of statistics[67]. This chapter discusses basic terminology used throughout the thesis.

Characteristic

A characteristic is an individually measured or observed value of an entity, e.g. the age of a patient or the distance between two points in space. To be able to compare measured characteristics, one needs the introduction of a scale, i.e. metric scale for

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[62] Gartzen 2012, p. 62
[63] Meissner 2009, p. 32
[64] Gartzen 2012, p. 62
[65] Geiger, Kotte 2008, p. 385
[66] Geiger, Kotte 2008, p. 385
[67] Arens 2015, p. 1340

distance. Finalising the topic of characteristics, for statistical significance expects a clear definition of the way of measurement and data gathering.[68]

Distribution[69]

The gathered values deviate amongst themselves, and the distribution describes their spread from the ordinary. Depending on the data gathered, different axes in diagrams offer better display of information. Chronological data for instance according to a time stream, qualitative characteristics in accordance with their groups. Furthermore, a distribution function shows quantitative data, especially when data suggests that the values follow a continuum.

Modus, Mean and Median[70]

A single answer to the question of the centre of a function proves difficult, as three different values can be referred to as the centre.

The modus is the value most observed, useful for qualitative data and questions like what is the most ordered product or similar.

The median is simply put the value in the middle, or in case of an even amount of measured values the median is determined by either both middle values, or the mean value between those two.

The last value is the mean value or average value. Depending on the value to be calculated, values vary. Summation of all values divided by the amount of values returns for instance the arithmetic mean. Other values may be the geometric mean or the logarithmic mean.

Range, Variance and Standard Deviation[71]

The mean value is never a satisfying answer on its own, as the deviation from it is essential for a thorough description of the representative information of the value. As such, the range is describing the difference of the biggest and lowest values. It is an easy number value, showing the spread of values measured.

The variance as such is the mean value of the squared deviations from the mean value. This value is the most important and researched value for value spread, and the square root of this variance is the standard deviation. If the measured values have the unit centimetre, the standard deviation therefore also has the centimetre as a scale. The importance of variances and standard deviations is especially important for basing choices depending on statistical analysis.

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[68] Arens 2015, p. 1340ff.
[69] Arens 2015, p. 1345ff.
[70] Arens 2015, p. 1350ff.
[71] Arens 2015, p. 1358ff.

Covariance and Correlation[72]

Measuring two values of an observed entity at once, gives the opportunity to see whether there is a relationship between those two values. The terms of covariance and correlation are the mathematical description of this relationship. The definition of covariance is the mean of deviations of two observed values of the same entity. It can take any value, and positive or negative values indicate a trend of the measured values, but they need standardisation in order to indicate on whether it is a strong or weak relationship. Hence, standardising the covariance provides the value of correlation, with it ranging from -1 to 1. This value gives an indicator, whether or not two values are influencing one another on a linear base. Quadratic correlation or trigonometric correlation functions will also provide the correlation factor of zero, and as such, comparison of the plotted data needs in a diagram provides any other possible dependencies.

2.3.5 Statistical Process Control

As described in Chapter 2.3.2 and before, stability and capability are different. Figure 2-8 shows this difference with four possible scenarios of process characteristics.

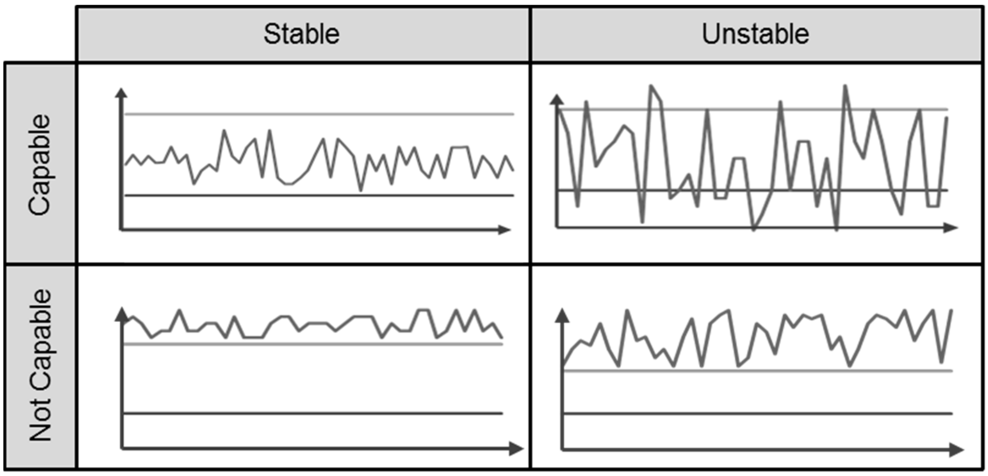

Figure 2-8 Different possibilities to describe the state of a process[73]

A process can therefore exist in four different states. State A being a capable stable process, which means the output is fulfilling the requirements and the variance of the process is under control[74]. The variables of the process are understood and can be adjusted to reach the desired outcome[75].

The principles of statistical process control (SPC) are needed to be understood, in order to describe the stability and capability by mathematical means. Both, are controlled by

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[72] Arens 2015, p. 1364ff.
[73] Based on: Geiger, Kotte 2008, p. 386
[74] Geiger, Kotte 2008, p. 385ff.
[75] Roger E. Bohn 1994

means of a control chart. AMSDEN offers a base approach on calculating values needed for that based on individual values.

Summarised, the formulas can be seen as the definition for the various values throughout this thesis. The variables used for stability calculation are defined as follows:[76]

$UCL_R \ldots\ldots\ldots\ldots Upper\ Control\ Limit\ Range$
$UCL_X \ldots\ldots\ldots\ldots Upper\ Control\ Limit\ individuals$
$LCL_R \ldots\ldots\ldots\ldots\ Lower\ Control\ Limit\ Range$
$LCL_X \ldots\ldots\ldots\ldots\ Lower\ Control\ Limit\ individuals$
$D_4 \ldots\ldots\ldots\ldots\ldots\ Factors\ for\ Control\ Charts$
$\bar{R} \ldots\ldots\ldots\ldots\ldots\ldots Average\ Range$
$\bar{\bar{X}} \ldots\ldots\ldots\ldots\ldots\ldots Average\ of\ individuals$
$R_i \ldots\ldots\ldots\ldots\ldots.\ Range$
$X_i \ldots\ldots\ldots\ldots\ldots..Measured\ Value$
$n \ldots\ldots\ldots\ldots\ldots\ldots Number\ of\ Values$

Only the values $\bar{\bar{X}}$ are individually measured values of the object investigated on. The rest of the values is calculated as follows[77]:

$$R_i = \left|X_i - X_{i-1}\right| \qquad \text{Equation 2-4}$$

$$\bar{R} = \frac{1}{n-1} * \sum_{i=2}^{n} R_i \qquad \text{Equation 2-5}$$

$$LCL_R = 0 \qquad \text{Equation 2-6}$$

$$UCL_R = D_4 * \bar{R},\ \text{with } D_4 = 3.268 \qquad \text{Equation 2-7}$$

$$\bar{\bar{X}} = \frac{1}{n} * \sum_{i=0}^{n} X_i \qquad \text{Equation 2-8}$$

$$LCL_X = \bar{\bar{X}} - (2.66 * \bar{R}) \qquad \text{Equation 2-9}$$

$$UCL_X = \bar{\bar{X}} + (2.66 * \bar{R}) \qquad \text{Equation 2-10}$$

The process is hence in a stable state when the measured values are not exceeding the upper and lower control limits. For determining stability by non-direct measurement, e.g. defects of parts, the usage of mean values is not possible. Here, the proposed method

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[76] Amsden et al. 1998, p. 34ff.
[77] Amsden et al. 1998, p. 69

is to use p (percentage), np (number of), or c (count) charts, each with their own set of calculation formulas[78].

In addition to the variables used for stability, capability calculation uses the following:

$US \ldots\ldots\ldots\ldots\ldots Upper\ Specification\ Limit$
$LS \ldots\ldots\ldots\ldots\ldots Lower\ Specification\ Limit$
$d_2 \ldots\ldots\ldots\ldots\ldots Factor\ for\ use\ with\ Average\ Range\ to\ determine\ \sigma$
$\sigma \ldots\ldots\ldots\ldots\ldots . sigma, standard\ deviation$
$6\sigma \ldots\ldots\ldots\ldots .. Tolerance\ Spread$
$UL_X \ldots\ldots\ldots\ldots Upper\ Limit\ for\ individuals$
$LL_X \ldots\ldots\ldots\ldots\ Lower\ Limit\ \text{for}\ individuals$

The specification limits are the boundaries of the process, the tolerated deviation from the mean value. UL_x and LL_x are representing the estimated largest and smallest individual values of the process, calculated by use of σ. Sigma itself is a statistical value. Now if the process demands a 3σ confirmation, the entire tolerance field needs to be inside the specification limits. d_2 is a factor representing a factor for control charts. If the number of samples is less than 3, then d_2 is defined as 1.128.[79]

The formulas to calculate the values are hence:

$$1\sigma = \frac{1\bar{R}}{d_2} \qquad \text{Equation 2-11}$$

$$LL_x = \bar{\bar{X}} - 3\sigma \qquad \text{Equation 2-12}$$

$$UL_x = \bar{\bar{X}} + 3\sigma \qquad \text{Equation 2-13}$$

$$6\sigma = \frac{6\bar{R}}{d_2} \qquad \text{Equation 2-14}$$

$$C_{pk} = \frac{\min(\bar{\bar{X}} - LS; US - \bar{\bar{X}})}{3\sigma} \qquad \text{Equation 2-15}$$

$$C_p = \frac{US - LS}{6\sigma} \qquad \text{Equation 2-16}$$

The determination whether or not a process is stable and capable is done by calculation of the indices C_p and C_{pk}. The C_p-value is an indicator for the capability, by calculating the tolerance of the process against the standard deviation[80]. Processes with values above 1.33 (concerning a tolerance spread of 6σ) are considered capable.

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[78] Amsden et al. 1998, p. 74ff.
[79] Amsden et al. 1998, p. 120ff.
[80] Amsden et al. 1998, p. 138

The second value, C_{pk}, indicates the location of the average of the process, and gives information on the minimal interval between the mean value and a tolerance. Its maximum value is the C_p value and should be bigger than 1.

2.4 Production Management

Production management is the entity steering the transformation process. Through adjusting control variables, the output of a process is determined. The process provides feedback in the form of data, and according to the information acquired different changes applied. Thus, production management in the form of a control loop is defined (Chapter 2.4.1). First, to control the process with knowledge, data needs to be gathered. Chapter 2.4.2 discusses the concept of data, information and knowledge, condensed to key performance indicators in Chapter 2.4.3. The last sub-chapter 2.4.4 discusses the basic implications of instable processes.

2.4.1 Definition of Production Management

The role of production management is to plan, steer and monitor the organisations resources[81]. As part of the business leadership tasks, it becomes evident that decisions need to be made systematically[82]. System control can be done in a control loop, with a constant or discrete comparison between an actual state and a target state[83].

The relationship between production management and the actual transformation can be seen in Figure 2-9. Production management is the steering entity of the production process with its own information input, output and references set up by the organisation. The executing entity, e.g. an assembly line, processes the input to output. By introducing disturbances to the system, the output values are differing from the target values, and the information is fed back to production management. Production management then adjusts the control variables to achieve a target and the loop is closed.

Production management can further be split up into three groups[84], according to the St. Gallen Management Model[85]. Since this thesis focuses on operative management, strategic and normative management are only briefly discussed. Strategic production management's role is to observe the environment of the company, understand possible risks and opportunities, and direct the focus of the firm towards future endeavours, while being compliant to the normative production targets. These two open the range in which operative management can act[86].

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[81] Günther, Tempelmeier 2014, p. 4
[82] Gutenberg 1951, p. 104
[83] Günther, Tempelmeier 2014, p. 4
[84] Dyckhoff 1994, p. 353
[85] Schuh 2014, p. 12
[86] Gienke, Kämpf 2007, p. 41

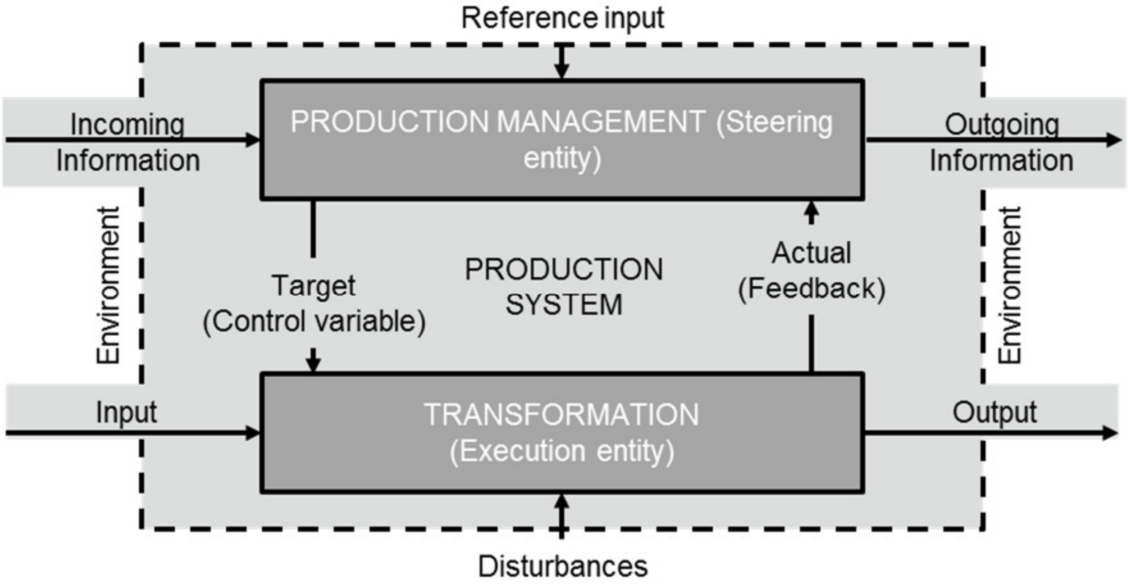

Figure 2-9 Production Management as the steering entity of a production system[87]

As the last steering entity above the level of transformation, operative production management's goal is to plan the effective output, acquire the necessary input, and define the transformation process[88]. The goals of operative management can be divided into market and company driven. On-time delivery, order to delivery time and capacity are those driven by the market, whilst the company tries to be as efficient as possible by increasing utilization and decreasing bound capital[89].

KLETTI compares production management to the principles of a control system. As such, he translates the controller to the Enterprise Resources Planning system (ERP), the production as the actuator of the system, which gives manual feedback to the system. Further elaboration on the system reveals that a purely ERP steered system is always driven by a delay, and data can only be provided on the past. To cover this inefficiency, Manufacturing Executions Systems (MES) were introduced, which enable a control over the process in real time.[90] Both of these systems are categorised as push systems, as management is "pushing" the production. In contrast to that, a Kanban system is a self-controlled pull system, as the ordering and production of goods is organised by the downstream process partners[91].

To efficiently steer and actually know what the consequences are, data alone is not sufficient. The gathered data first needs analysing, in order to have an understanding of possible results.

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[87] Translated from German: Dyckhoff 1994, p. 352
[88] Dyckhoff, Spengler 2010, p. 10
[89] Schuh 2014, p. 20
[90] Kletti, Schumacher 2014, p. 15
[91] Wiendahl et al. 2009, p. 94

2.4.2 Data, Information and Knowledge

In order to manage something, it first needs to be measured. This famous saying can be traced back to Lord Kelvin, and can be seen as a universally applicable fact[92]. However, BOHN further intensifies the necessity to first transform the gathered data into information, and then interpret the to gather knowledge.

Data can be described as the pure stream of measurements, e.g. the results of a tension test. By transcribing this data into a chart, information is acquired as a connection between elongation and applied forces. However, this information does not result in any predictions or causal associations. These predictions or associations would be what is described as knowledge[93]. The understanding of the information and deriving actions and predictions from this.

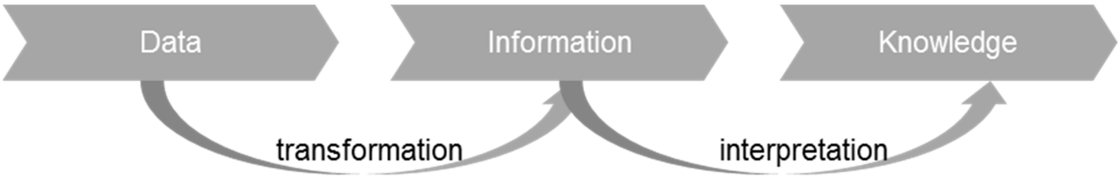

Figure 2-10 Transformation from data to knowledge

Since highly complex production systems produce high amounts data, to acquire knowledge in the end, the information out of measured data needs to be condensed. An effective way for this are key performance indicators.

2.4.3 Key Performance Indicators

With the introduction of key performance indicators to companies, management of processes was streamlined, as they deliver exact and condensed information on the current state. Without having effective indicators, or even further effective KPI-Systems, companies cannot be steered through changing times without many resources.[94]

In manufacturing, the emphasis on what measures are important differed throughout the times. During the early post World War 2 era, cost measurements were the main criteria, changing towards productivity and quality measurement until in the 1990s multi-dimensional measurement started to evolve[95].

Performance indicators can be categorized differently, and using the correct indicator is essential for having a correct statement concerning the business. HON delivers a way of categorization by means of targeting different performers according to time[96]. Figure 2-11

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[92] Roger E. Bohn 1994
[93] Roger E. Bohn 1994
[94] Preißler 2008, p. 3ff.
[95] Hon 2005, p. 139
[96] Hon 2005, p. 141ff.

shows seven purposes of performance measure, with the possibility of looking back and ahead, the concept of lagging and leading indicators is established.

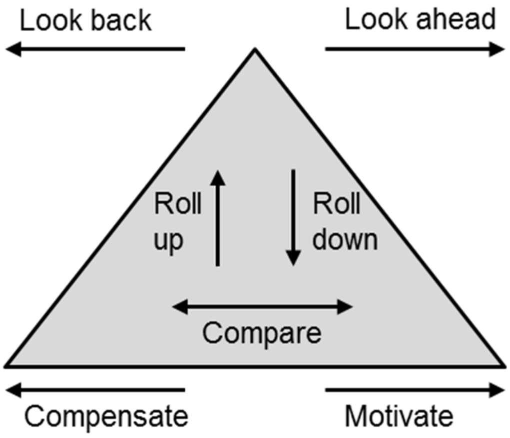

Figure 2-11 Seven purposes of a measurement system[97]

The focus on backwards oriented indicators is used a lot by finance, as the profit, return on investment and others are calculated at the end of a period. This results in indicators, which give no suggestion regarding strategical decisions[98]. Leading indicators deliver a different approach, as they try to indicate future problems, for instance the current level of employee training.

Another system to classify KPIs is by their mathematical properties[99]. Figure 2-12 shows the distinction by absolute and relative values. The absolute group includes all that directly counted values and those calculated with simple arithmetic operations, for instance profit being the difference of income and costs. Absolute values are usually not as effective, as the relation to the total amount is not given. For instance having produced 100 defective products has a different impact on the business if it produces only 100 units or a million. Hence, the usage of relative KPIs is to be preferred[100]. These numbers provide ratios, and are grouped by the correlation of the numerator and dominator. The first group consists of those where the denominator is included in the nominator, e.g. defect products vs. total products produced. The second group provides information on numbers given as characteristics of the same base, i.e. the equity-to-debt ratio. The last group compares the same numbers during different periods, for instance the production output of two shifts. Nevertheless, in some situations the absolute numbers are also important, for instance when reporting on health and safety related incidents.[101]

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[97] Hon 2005, p. 142
[98] Preißler 2008, p. 3
[99] Preißler 2008, p. 12ff.
[100] Bomm 1992, p. 23
[101] Sejdic 2014, p. 609

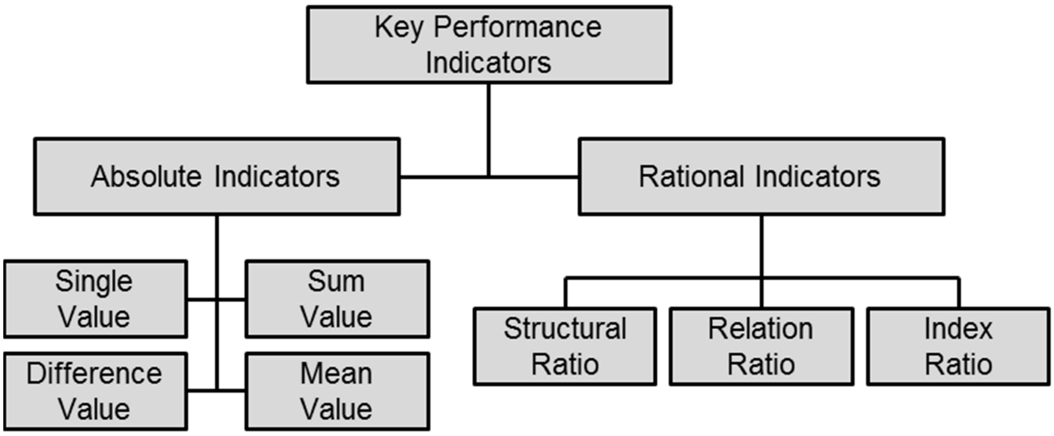

Figure 2-12 Categories of KPI according to PREISSLER[102]

Above all, the significance of KPI is highly dependent on the quality of the data it is based upon. Faulty indicators or not well-understood ones give no diagnostic value to the user, and management can easily dismiss them[103]. In consequence, every indicators needs to follow the base rules. These are in accordance to REICHMANN[104]:

- Informative character
- Ability of quantification
- Specific form of information

The informative character is the function of an indicator, to provide detailed information and enable the user to base decisions on that. Quantification is the ability of variables to scale up or down, and consequently provide detailed statements. The specific form is needed to reduce complex structures and processes to have a simple overview in management. Given these points, the necessity for clear KPI to control and steer production effectively is apparent.

2.4.4 Cross Functional Impacts of Disturbances

In the context of a factory, the cross-dependence of the logistics and production system cannot be neglected. For both to function properly, a stable condition is required. The predominant factors for a smooth assembly are part supply and assembly work[105]. Assembly managers tend to drive the responsibility for missed production towards logistics, by stating parts availability as the only reason for missed production volume.

On the one hand, this is correct, as missing parts are the main source of interrupted productivity, but the second major factor is actually the design of work[106]. In addition to the negligence to the design of work, assembly has a direct impact on logistics

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[102] Based on: Preißler 2008, p. 12
[103] Bomm 1992, p. 29
[104] Reichmann 1997, p. 19ff.
[105] Köhler 1997, p. 16ff.
[106] Baudin 2002, p. 6

performance. Additional issues rise up, as the usage of parts from the service area, without notifying logistics leads in return to missing parts at the end of production. In some cases, the actual bill of materials is missing parts, or in other cases demanding parts not being produced anymore. [107, 108]

With increase and instability of assembly time, logistics is unable to cope as easily with fluctuations and further upstream those fluctuations increase even more. This effect is the so-called bullwhip effect, introduced by LEE[109]. The term describes the before mentioned fluctuation in demand and order quantity for the regular consumer market, but the concept is valid for all process partners further upstream. Notably, the consumption of goods is at a steady state, but customers order in larger batches, resulting in high storage quantities, production backlogs and other issues. As the issues start at a plant, the order received by the supplier happens in a steady state, resulting in an up and down of production volume due to changing forecast. To counter this effect, literature agrees on the necessity of informing all process partners as fast as possible in case of changing demands, and a decrease orders size[110].

Especially during ramp-up, these disturbances occur on a regular basis, as production systems are not matured and parts are re-engineered regularly, resulting in parts missing or being damaged. Introducing new models and variants to the same assembly line increases the probability to pick and assemble the wrong part[111]. Many tools of the lean methodology give a possible solution, but not all need to be implemented. One base approach is to increase the part commonality as high as possible, and for those not able to, differentiate them to the highest feasible degree and physically eliminate the danger of wrong assembly, also known as Poke-Yoke.

Another issue following instable production and logistics is the fitment of parts after the production, leading to additional damage on parts, increasing even further the pressure on the logistics system.[112]

While these issues occur in a low frequency, the introduction of new products introduces additional disturbances.

2.5 Ramp-Up

The period between product development and series production is called ramp-up. It is a phase of instability, high complexity and constant change[113]. Production fails to adhere to the given parameters; deviations and firefighting are daily operations. The following

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[107] Köhler 1997, p. 16ff.
[108] Baudin 2002, p. 9ff.
[109] Lee 1997
[110] Arnold et al. 2008, p. 30ff.
[111] Baudin 2002, p. 223
[112] Berg 2007, p. 23
[113] Gartzen 2012, p. 70

Sections give an overview on this phase, starting with the definition in Chapter 2.5.1. Chapter 2.5.2 further extends the information given in previous Sections with ramp-up specific challenges.

2.5.1 Definition of Ramp-Up

As mentioned, ramp-up is the phase between development and full capacity series production[114]. The necessity for a change can have various root causes, both wanted and unwanted. The introduction of a new product, interruptions resulting from disturbances, or just increasing production volume trigger a ramp-up[115]. As a linkage between the design and factory, the phase is critical for understanding the product and early problem solving[116].

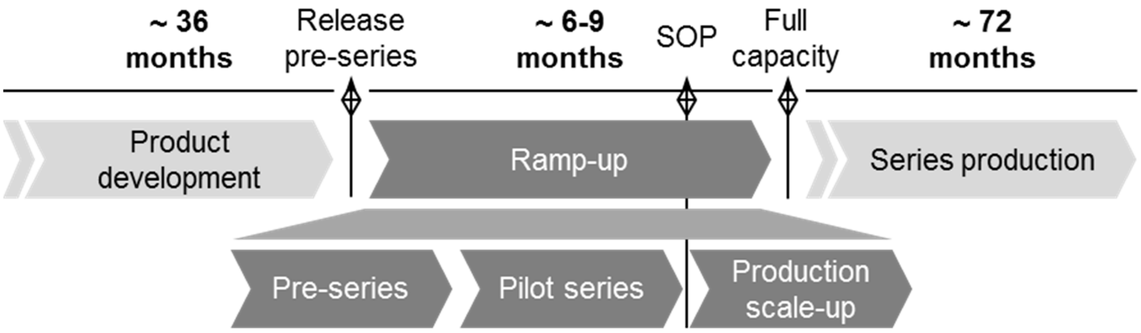

Figure 2-13 Ramp-up phases in the automotive industry according to SCHUH[117]

While research has dealt and defined the phases before and after the ramp up[118], the ramp up itself is still a young field of interest. Managers find themselves in a state of losing control, as the introduction of highly complex products and quick responses to market needs results in more ramp-ups, in shorter time intervals and to higher scale than ever before. Studies have shown that customers expect high quality starting with the first product, but as the ramp-up period encounters a high amount of disturbances those requirements are not met[119].

Figure 2-13 shows a split up of the ramp-up phase as observed in the automotive industry. Some literature refers to ramp-up as only the scale-up phase, while most German literature includes the building of the first prototypes as well[120]. The term pre-series refers to the first production of prototypes on a larger scale. Processes are still not according to series, and delivered parts are not made from series tooling[121]. Companies,

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[114] Terwiesch, E. Bohn 2001, p. 2
[115] Berg 2007, p. 1
[116] Schuh et al. 2008, p. 10
[117] Translated from German: Schuh et al. 2008, p. 2
[118] Schuh et al. 2008, p. 2
[119] Berg 2007, p. 98
[120] Zeugtrager 1998, p. 81
[121] Schuh et al. 2008, p. 12

who fail to understand their product during this phase, tend to exceed the project costs[122]. Following pre-series, pilot series or null series production starts. The integration of the production is done at the series production location, and tools and parts should have series maturity. Deviations and process changes still occur, but on a smaller scale[123]. Finalising towards series production is the start of production with the "job no. 1" followed by a scale up towards full capacity. Ramp-up is finalised when quality and quantity reach a specified target, highly depending on a company's policy[124]. These targets are only achieved when entire staff is trained and throughput times stabilised[125].

ZEUGTRAEGER analysed the different requirements during the phases mentioned above, and concludes the targets to be achieve differ from one phase to another. During the first phase, quality is the primary goal. Hence, the so-called quality phase's focus lies on finding problems, understanding issues and ensuring that functions are securely performed. Not before stabilising on a level of productivity should the focus be on volume. During Phase 2, the volume phase, the system capability is tested. Production is still subject to changes, but achieving high output numbers is the target. He concludes in phase 3 being the one where money is starting to be earned, and by thoroughly eliminating previously raised problems and improvement of the processes, the time to full capacity is reduced.[126] The trade-off between volume and try-out should therefore be in favour of try-out in early phases, later shifting towards volume[127] [128].

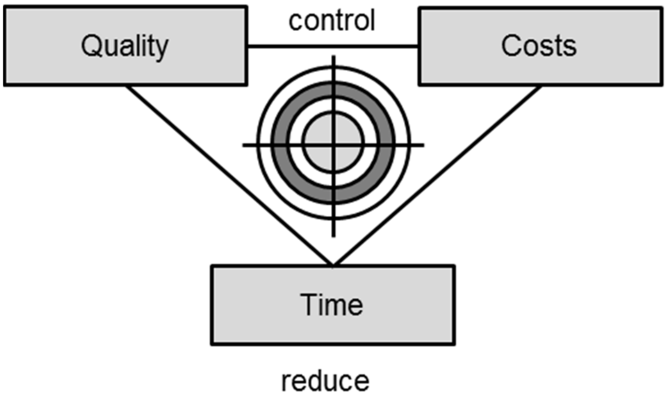

Figure 2-14 Target values during ramp-up[129]

The three phases also translate to the targets of ramp-up. Figure 2-14 shows quality and costs as targets to be controlled, while time needs to be minimised. It can be summed up as quality of the product needs to be achieved as soon as possible by using as little

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[122] Clark, Fujimoto 1991, p. 121
[123] Wangenheim 1998, p. 27
[124] Wangenheim 1998, p. 30
[125] Hahn 1999, p. 612ff.
[126] Zeugtrager 1998, p. 81ff.
[127] Terwiesch, E. Bohn 2001, p. 7ff.
[128] Clark, Fujimoto 1991, p. 176ff.
[129] Based on: Schneider 2002, p. 514

resources as possible. It becomes clear that it is difficult to meet all three targets at once, which is why production management and Advanced Product Quality Planning (APQP) become an integral part of the process.[130]

GUSTMANN argues that there are six basic criteria for a ramp up process[131]:

- Throughput time for products
- Output quantity for processing units
- Input material
- Unit costs
- Cycle time and takt time
- Quality parameters

These form the integral parts of key indicators for process control. By managing these targets, success can be ensured and disturbances dealt with accurately.

2.5.2 Influencing Factors on Ramp-Up

Effective and controlled ramp-up is a key to an economically successful launch of a new product. Occurring challenges and differing targets result in high costs, which cannot be earned easily back in today's volatile and fast changing market, hence an effective management needs a profound knowledge on the factors for a successful ramp-up. To install effective solutions and mitigations, success factors include a universality of the ramp-up phase, understanding of the production ramp-up as a complex field, and the effective direction of the influences[132]. This chapter focuses on these factors and discusses the theory for successful launches.

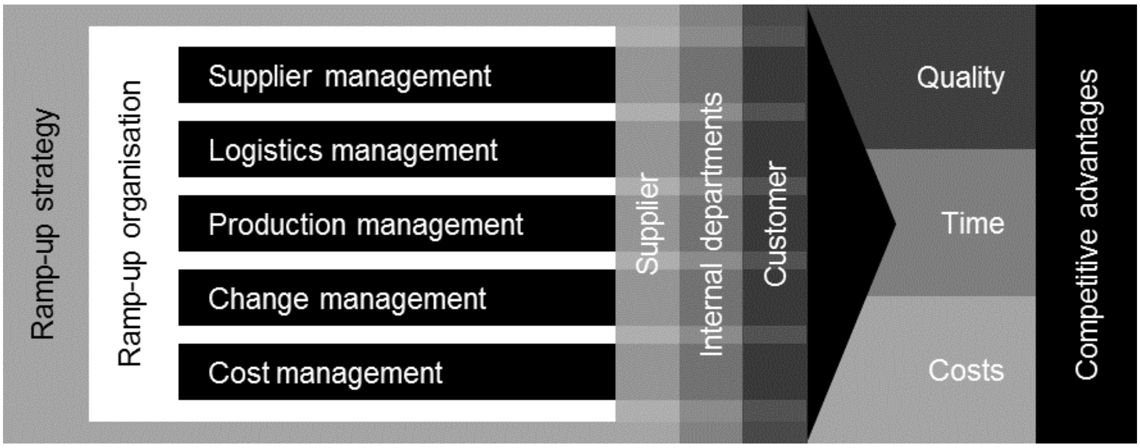

Figure 2-15 Scope of integrated ramp-up management according to SCHUH[133]

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[130] Schneider 2002, p. 515
[131] Gustmann et al. 1989, p. 16
[132] Gustmann et al. 1989, p. 31
[133] Translated from German: Schuh et al. 2008, p. 4

As depicted in Figure 2-15, to achieve the previously discussed targets of a ramp-up, various stakeholders are needed to achieve the full competitive advantage. Supplier and logistics management play a role in actually bringing the correct parts to the line, while production management needs to enable and train associates for future products. Change management needs to be thoroughly transparent to all participants, as last-minute changes translate to disturbance at the production line. Finally, cost management targets to keep all expenses in check and monitor whether the project adheres to the budget. These five entities form the core of the ramp-up organisation, which follows the according strategy.[134]

The strategy is a core element of the company, and determines future processes and product structure[135]. The strategy is the general guideline and specifies the period during which the production starts, ranging from few months for a hard disk, to several years for a new airplane[136]. As the linkage between development and start of production, the ramp-up strategy is highly influenced by the strategies of these phases. Controlling takes a crucial role in supporting the harmonisation of interfaces[137].

Disturbances resulting from the friction at the interface, as well as in outsourced and simultaneous processes results in a delay of series production leading to higher costs and lost income[138]. These disturbances have a possible impact not only on the launch project, but in case of large factories can have a serious impact on series processes. WANGENHEIM identifies several possibilities to reduce this friction, and proposes an intensified project coordination by controlling through maturity modelling.

As products become more complex, integrating critical suppliers is one way to enable successful industrialisation[139]. Although the products vary throughout the industries, the realisation project is always challenging for companies. Changes in processes are often part of a new product architecture, and further increase the complexity of the phase[140]. KUHN ET AL. identify five aspects in the field of action for ramp-up management[141]:

- Planning, controlling and organisation
- Product change management
- Production system
- Cooperation and references
- Knowledge management and qualification

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[134] Schuh et al. 2008, p. 4ff.
[135] Schuh et al. 2008, p. 9
[136] Terwiesch, E. Bohn 2001
[137] Wangenheim 1998, p. 1
[138] Wiendahl 2002, p. 653
[139] Schuh et al. 2008, p. 9ff.
[140] Wiendahl 2002, p. 653
[141] Kuhn 2002, p. 17

For further discussions, this thesis focuses on production management and improving the production system and controlling, with references to logistics management as part of the production system (referring to Chapter 2.1.4).

Categorisation of ramp-up factors helps with a pre-emptive understanding of the ramp-up process and enables finding effective counter measures. GUSTMANN defines the influencing factors as[142]:

- Degree of novelty
- Degree of complicacy
- Level of production preparation
- Level of capable work
- Level of production execution

These factors have cross-effects, and solving is only possible in their entirety. These cross effects are shown in Figure 2-16 . Leadership and planning are paramount skills to manage the problems, which are hence not depicted as criteria.

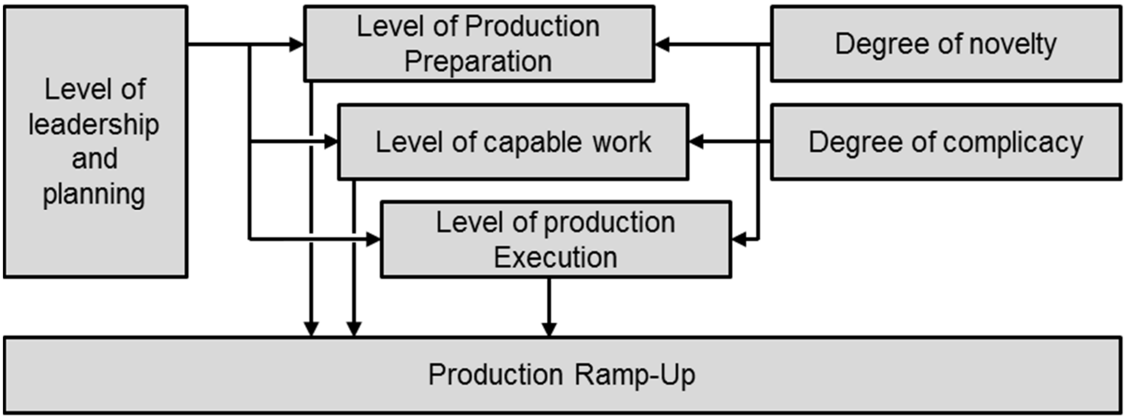

Figure 2-16 Cross-influence of factors during production ramp-up[143]

To wholly understand and control this the ramp-up, extensive experience and knowledge is needed, usually exceeding the knowledge of single individuals[144]. The control and expected ramp-up curve depend highly on the company's chosen strategy, as well as the factors "Human, Technology and Organisation[145].

2.5.3 Ramp-Up as an Unstable System

One key problem when managing a ramp up phase is the low level of knowledge of problems and the amount of data provided[146]. To have the information whether a process is stable or not, the negated state can be derived for an easier understanding of the

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[142] Gustmann et al. 1989, p. 39
[143] Translated from German: Gustmann et al. 1989, p. 53
[144] Schuh et al. 2008, p. 3
[145] Heins 2010, p. 16ff.
[146] Wiendahl 2002, p. 653

process. GARTZEN defines ramp up systems as unstable since all instability characteristics are present.[147] In Figure 2-17 a description of the criteria mentioned above is given on the left side, on the right side the observed characteristics for Ramp-Up are provided.

During ramp-up, an organisation is experiencing various forms of disturbances, which cannot be handled within the usual frame of action. Management struggles to find an approach that will ensure achieving the targets, and being in a state of constant change, an overview is easily lost. The knowledge of product and process is not fully developed, and hence, adjusting parameters can have a high effect on the output. Disturbances are occurring regularly due to underlying issues, and knowledge reaches a high enough level only through time.[148]

The state of instability can easily be determined by observing these items, and postulating from these conditions, the ramp up is stabilised once none of the above is present. Out the points mentioned, two need a more detailed discussion for this thesis, as the concept of learning curves is essential for understanding the progress towards process maturity[149], and a proper change management system is an enabler of stability[150].

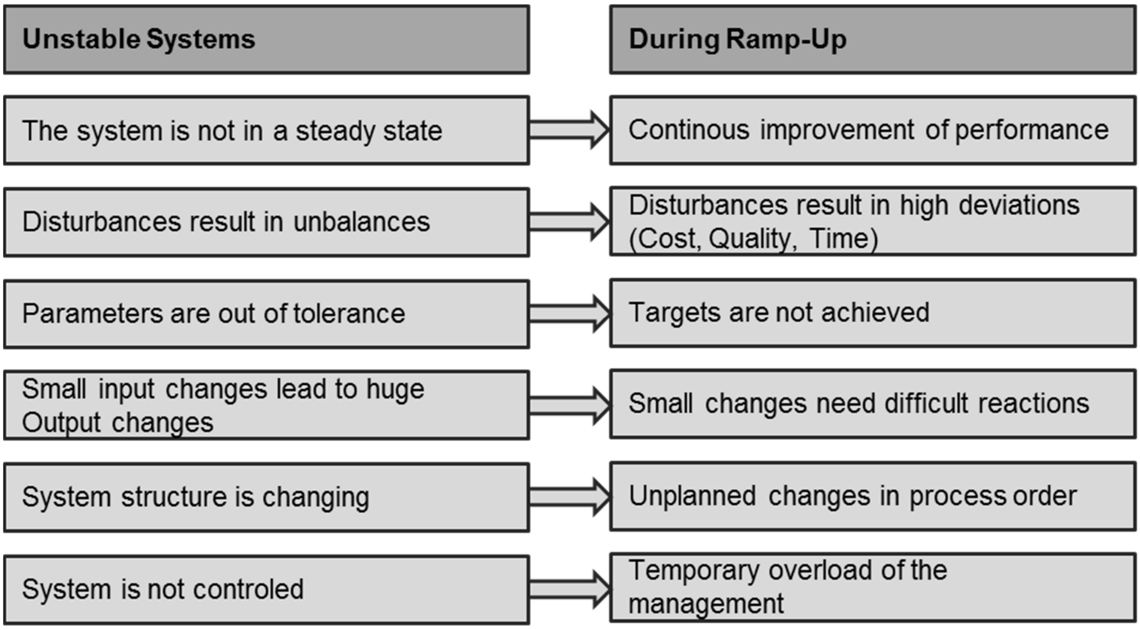

Figure 2-17 Characteristics of an unstable system[151]

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[147] Gartzen 2012, p. 75
[148] Gartzen 2012, p. 73ff.
[149] Terwiesch, E. Bohn 2001, p. 9
[150] Schuh et al. 2008, p. 215ff,
[151] Based on: Gartzen 2012, p. 73

2.5.4 Learning Curve Theory

As a product passes through its lifecycle, the knowledge of staff is increasing, often described by the *learning curve* or the *law of production learning*. The first introduction of a mathematical function dates back to T.P. Wright in 1936. By observing the effort for manufacturing in the airplane industry, a definition of a power curve was provided:[152]

$$y = a * x^b \qquad \text{Equation 2-17}$$

Out of the initial effort "a", multiplied with the units produced "x" and powered by a coefficient "b", the average effort for a unit y can be estimated. The introduction of the coefficient "b" describes in the case of ramp-up the so-called ramp-up coefficient. The research by GUSTMANN[153] was mainly analysing previous ramp-ups, and thus deriving expected values for future ones.

By further comparing various approaches from different authors, ULLRICH concludes that the optimal description of the learning curve must include a terminal value that cannot be further improved upon, and the experience of the workers must be taken into consideration. The formula is therefore more sophisticated for the use during ramp-ups, and will be used as the standard formula for learning curve descriptions for assembly time throughout this thesis[154]:

$$t(x) = k + (m - k) * (x + B)^b \qquad \text{Equation 2-18}$$

The term "k" is describing the irreducible content of the effort, e.g. the base assembly time. The second factor "m" is thus describing the captured value of the first piece introduced, replacing the factor "a" from the previous equation. "B" is the factor taking the previous knowledge of the staff into consideration. The value for "B" needs to be estimated, and is highly dependent on the organisation itself.

2.5.5 Change Management

During the introduction of a new product, the organisation is in a state of change[155]. The introduction of changes does not need to be further discussed on a higher level of management, and employees are aware of the changes necessary. Nonetheless, the new product comes with its set of challenges, and in an environment of constant change, overview can easily be lost on which changes have been implemented and which not[156].

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[152] Ullrich 1995, p. 12
[153] Gustmann et al. 1989
[154] Ullrich 1995, p. 45
[155] Risse 2003, p. 218
[156] Schuh et al. 2008, p. 215

General change management can be described with the 8-step method of KOTTER[157]. A basic guideline for effective implementation of adaptations is introduced. Depending on the size of changes to be implemented, some steps can be omitted. The importance lies on the documentation and the making the changes durable long enough.

SCHUH on the other hand introduces change management only under the aspect of late engineering changes and process deviations. Those two are defined as the main drivers of change during the ramp-up, and depending on it being in the field of engineering or production, the responsibilities need to be clarified on who is actually implementing the change.[158]

Every change of a process is done because of primary reason, during series as well as during ramp-up. Although changes occur frequently, the achievement of this reason then needs to be monitored. For instance if the reason for the change is to save time, the measurement of the previous time vs. the new time can be taken into consideration. Monetary and other reason can be taken into consideration in the same way, by comparing the state before to the new one. The effort can then afterwards be compared to the result, and a decision can be taken, whether or not the change should be implemented. The same monitoring system applies to material flow changes.

2.6 Manufacturing Industry

After introducing production systems and processes in previous Chapters, the following focuses on manufacturing companies and their specifications. Chapter 2.6.1 provides a basic definition of manufacturing companies. The second sub-chapter discusses the goals of manufacturing companies and Chapter 2.6.2 sets the context of the research within low volume production.

2.6.1 Definition of Manufacturing Companies

Manufacturing companies can be distinguished in various ways, mainly by production type and volume. This chapter introduces the classifications and variations.

The most basic system of manufacturing is a single machine or workstation. Products that are more complex need a sequence of different workstations to be realised. This chain of production can be realised as a batch production, or in the case of high volume production, a flow line is the more suitable solution[159]. Zooming out further from this, the factory including the design, planning, programming etc. comes into sight. In case there

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[157] Kotter, Cohen 2002, p. 4ff.
[158] Schuh et al. 2008, p. 239ff.
[159] Hon 2005, p. 142

are suppliers, the factory is situated in the heart of a production network as the highest level of the company[160].

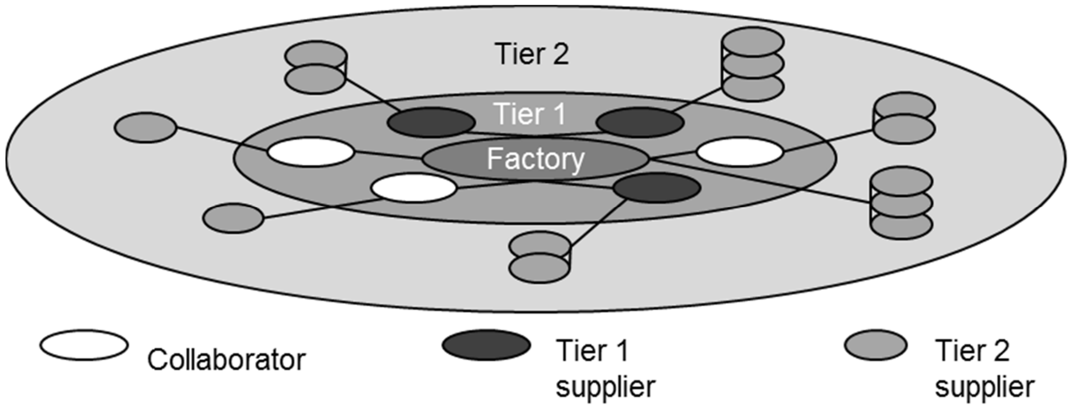

Figure 2-18 Centralised production network with suppliers and collaborators[161]

Figure 2-18 shows such a production network, with a 2-tier supplier system and integrated collaborators. Collaborators have an extended responsibility, as they can be integrated in an early phase of development, and have higher impact on the factory's decisions. In the last years, this approach of horizontal relationships has gained attention, as the specialisation of companies towards their core competences increases[162]. This transformation towards outsourcing, started in the 1990s, and lead ultimately to the necessity of supply chain management[163]. Dealing with increased complexity of production networks, recent years show active support of decentralized manufacturing. The impact on the current situation is yet to be proven, and cannot be anticipated today[164].

The factory itself can be further classified by the criteria shown in Table 2-1. On the left, the distinguishing elements can be examined. The two not in previously defined criteria are the production volume and the vertical division of labour.

Briefly described, the production volume is determined by the repeatability of the process steps in accordance to the product. This classification according to production volume can be seen in Figure 2-19. Low volume production was defined with its throughput time being higher than 16 hours, and the volume being less than 25 units daily[165]. This definition is seen too general, as lot sizes are not taken into account[166].

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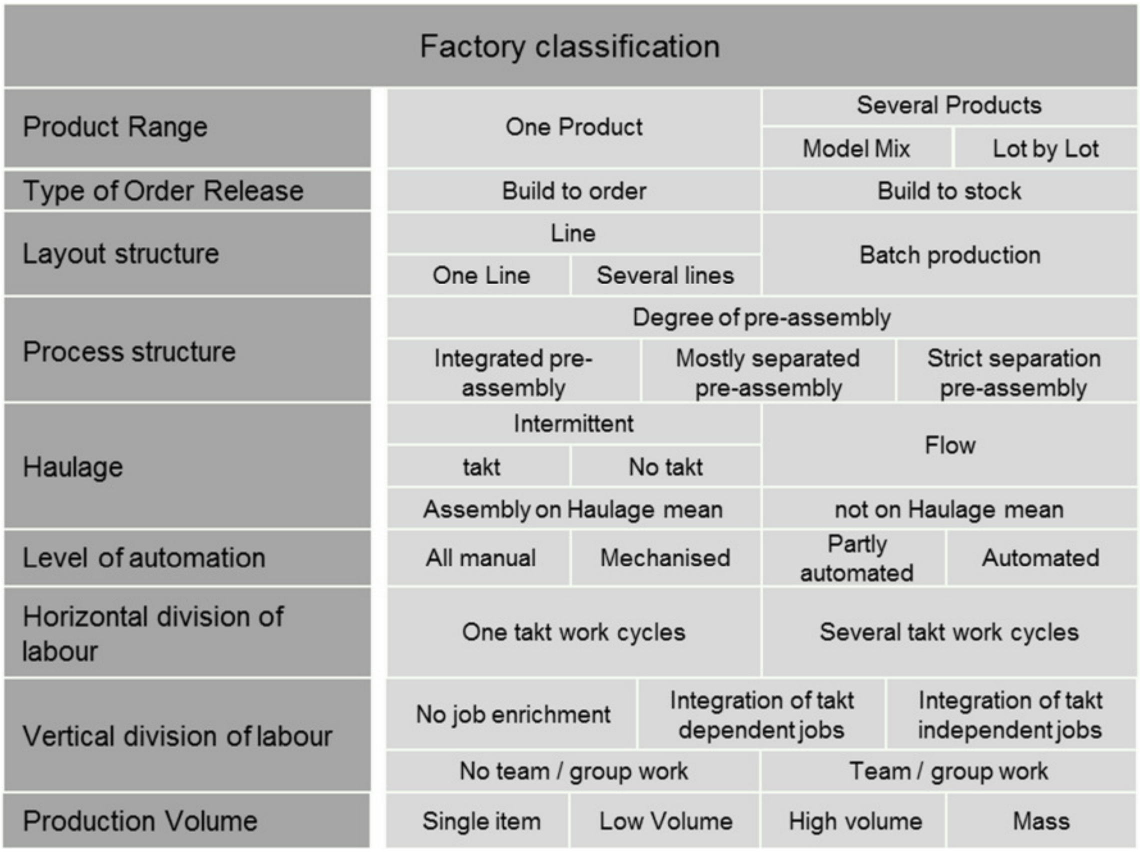
[160] Wiendahl et al. 2007, p. 785
[161] Based on: Hon 2005, p. 142
[162] Werner 2013, p. 99
[163] Wiendahl, Lutz 2002, p. 574
[164] Kendrick et al. 2017, p. 68
[165] Schomburg 1980, p. 70ff.
[166] Köhler 1997, p. 7



Factory classification				
Product Range	One Product		Several Products	
			Model Mix	Lot by Lot
Type of Order Release	Build to order		Build to stock	
Layout structure	Line		Batch production	
	One Line	Several lines		
Process structure	Degree of pre-assembly			
	Integrated pre-assembly	Mostly separated pre-assembly	Strict separation pre-assembly	
Haulage	Intermittent		Flow	
	takt	No takt		
	Assembly on Haulage mean		not on Haulage mean	
Level of automation	All manual	Mechanised	Partly automated	Automated
Horizontal division of labour	One takt work cycles		Several takt work cycles	
Vertical division of labour	No job enrichment	Integration of takt dependent jobs	Integration of takt independent jobs	
	No team / group work		Team / group work	
Production Volume	Single item	Low Volume	High volume	Mass

Table 2-1 Possible categories for factory classification[167] [168]

KOEHLER finalises his definition as being not discrete, and with increasing series character, the production flow transforms into a continuous state. He further discusses the possibilities to achieve higher commonality by introducing model range approaches and model kit systems, as opposed to the single item production.

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[167] Dürrschmidt 2001, p. 21

[168] Gottschalk 2006, p. 14

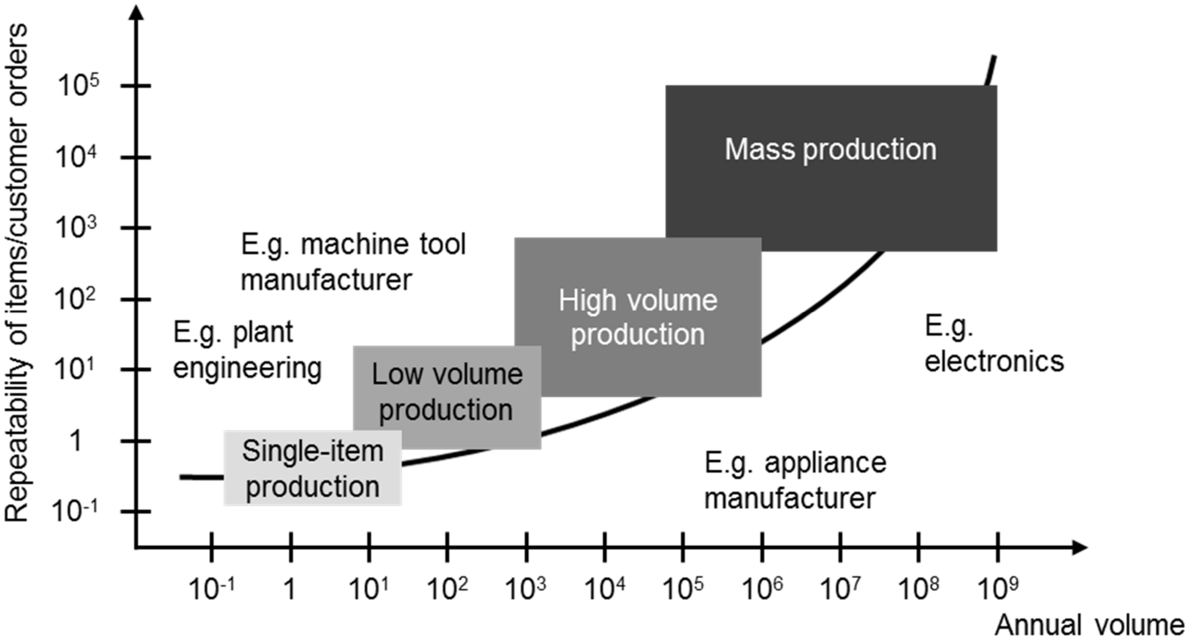

Figure 2-19 Classification of production systems depending on production volume[169]

2.6.2 Low Volume Manufacturing Systems

As a result of customers individualising their products, production is shifting away from high to a low volume production. With the introduction of the concept of mass customization, new challenges for assembly occur. Not only are these challenges applying to former mass producers, but also to small companies, that feel the pressure of a globalised economy. The increase in productivity is the go-to solution for these problems, resulting in a decrease of focus on the throughput time towards higher flexibility[170].

Current developments in the target markets consequently lead to a change in the mind-set of producers. Differentiation and individualisation in a produce-to-order market resulted in products that cannot be switched between customers. Production to stock is reduced to a minimum, and the ability to implement last minute changes is considered a competitive edge[171].

With the introduction of new variants and models, low volume systems start to compete against earlier mass producers, without having the expertise of fast ramp-ups. Thus, by trying to become faster in introducing new products to the markets to sustain a healthy business, companies struggle with the changes.[172]

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[169] Translated from German: Eversheim 1989, p. 11
[170] Fleischer 2008, p. 758
[171] Köhler 1997, p. 7
[172] Kuhn 2002, p. 10

Mass producers on the other hand face a different challenge. Formerly producing large numbers of products they saw the use of automation wherever possible. By having fewer numbers, those investments are not returning the same profit, and a higher degree of manual work is needed. This further triggers a higher degree of qualification of the associates, and an increase in takt time and tolerance of assembly times.[173]

2.7 Automotive Manufacturing

With the introduction of new models and derivatives on a nearly monthly base, especially the automotive industry has to perfrom fast ramp-ups due to changing markets. New modes of transport, introduction of new propulsion systems, increase of material variety all lead to challenges for production. Another trend is the change of the amount of value added content from the OEMs, as they tend to offer more services exceeding their past market of pure manufacturing, whilst outsourcing everything not considered a core competency.[174]

Chapter 2.7.1 defines the boundaries of the automotive industry, transferring to the challenges in Chapter 2.7.2. The final chapter (2.7.3) provides information specifically on the ramp-up process in the automotive industry.

2.7.1 Definition of Automotive Industry

The automotive association of Germany refers with the term automotive industry to producers of engines, motor vehicles and trailers as well as parts and accessories[175]. Literature expands the definition further and includes further downstream businesses[176]. Differentiation is done between car manufacturers and suppliers.

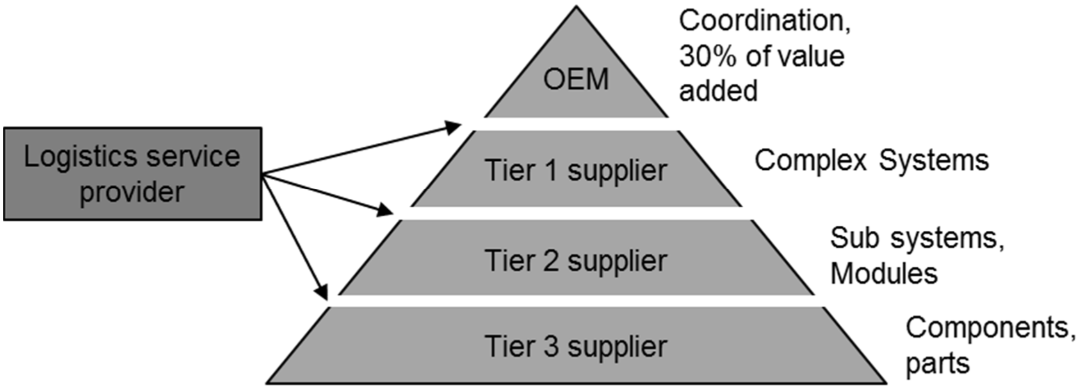

Figure 2-20 Hierarchy of OEM and suppliers in the automotive industry[177]

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[173] Eversheim 1989, p. 11
[174] Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag 2012, p. 7
[175] Verband der Automobilindustrie
[176] Wallentowitz et al. 2009, p. 1
[177] Translated from German: Wallentowitz et al. 2009, p. 2

Original equipment manufacturer are the producers and developers of the product to the end user market. In case of the automotive industry, this refers to the brand manufacturer.

Suppliers are all those partners, who provide services to the downstream process partners. They can be further split in dependence on their tasks e.g. development, production or combination of those two, or as in Figure 2-20 in dependence of their hierarchy towards the OEM.[178]

As Literature points out, the industry is in a state of change, and models of cooperation are changing. Some suppliers take over the entire development and production of complex systems, while manufacturers new to the industry (e.g. Tesla) are questioning the supremacy of established ones. Size will not matter as much as the ability to react quickly to changes[179].

2.7.2 Challenges in Automotive Engineering

For years, car manufacturing was considered a typical example of mass production. While the units produced are still showing number of high volume, the variation and customer specific options lead to an increase in models[180]. By today, a premium manufacturer offers their customers a possibility of 10^{31} variations[181], with non-premium following close by. This type of customer individual mass production is referred to as mass customization[182].

Production figures range from up to 3000 units a day for compact cars while for sports and executive cars less than 100 seems to be the production volume. Luxury car manufacturers even produce less, their figures closing in on the volumes of special utility vehicles (<20 units per day)[183]. While economies of scale used to thrive on lowered cost effects and increasing output due to learning, with every variation and derivative these effects are lowered. OEMs counter these measures by introducing mixed model lines and fast setup changes, resulting in difficulties for logistics as parts variability increases[184].

Due to the saturation of the markets and new competitors from Asia as well as new technologies, pressure on the market increases and OEMs find themselves in a situation where the introduction of new technologies and products is the only way to economic success[185].

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[178] Wallentowitz et al. 2009, p. 1
[179] Günthner 2007, p. 5
[180] Ihme 2006, p. 9
[181] Günthner 2007, p. 4
[182] Gilmore, Pine, B. Joseph II 1997
[183] Ihme 2006, p. 9ff.
[184] Günthner 2007, p. 19
[185] Tücks 2010, p. 14

2.7.3 Ramp-Up in the Automotive Industry

The motivation to produce more products within shorter time urges automotive companies to increase their organisational capabilities and handle product launches in a shorter time-period. Compared to product life cycles of up to 17 years in the past, today's short-lived products of 5-6 years lead to a decrease of time for profit[186].

The ramp-up strategy of an OEM targets the reduction of the time to market and increasing the capacity usage (time to volume)[187]. Research leads to the conclusion that few companies actually achieve all targets set[188]. Only a third of all ramp-ups seems to be on spot, and most companies are overwhelmed by solving quality, time and cost related problems at start of production[189].

Companies identify their weaknesses in introducing new products, and demand for standardised and synchronised processes during the ramp-up phase is given[190]. Economic success is driven by the response to quick changes[191], and stabilisation of assembly time is a core demand for introducing the product on a mixed model line[192]. Previously, car manufacturers have defined the readiness for production by observing quality and rework figures. With the increase of variants and the resulting decrease of testimonials, the standard approaches of statistical process control and determination of product maturity need to be re-designed. The ramp-up itself needs a tailored ramp-up production control, including means of risk management[193].

Concluding, a structured approach in this environment should therefore focus on a low volume production system, being able to gather necessary data efficiently. The implementation of various changes needs coordinating, and as time deviations are of high criticality on a multi-product assembly line, fast feedback is required. Resulting from a multi-project landscape, a mixture of new projects being in their own ramp-ups at the same time gives the possibility to compare and learn from each other. Covering this by means of a holistic solution, being able to transcend the boundaries of a single project and ramp-up phase, enables vital feedback for future products to come. Finally, to keep the costs in check, the concept of frontloading was introduced to the industry. The same concept can be adapted to risk management, by anticipating where problems might occur.

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[186] Jürging 2008, p. 9
[187] Schuh et al. 2008, p. 10
[188] Kuhn 2002, p. 2
[189] Fitzek 2005, p. 7
[190] Kuhn 2002, p. 2
[191] Kuhn 2002, p. 21ff,
[192] Heike et al. 2001, p. 104
[193] Kuhn 2002, p. 22ff.

3 State of the Art

Justification of a research effort is primarily based on a research gap by comparing existing solutions. For this reason, a thorough investigation of state of the art literature is performed, and following up on the basic principles of process, stability and ramp-up from Chapter 2; a discussion of the solutions is presented.

Firstly, general approaches for measuring instability and waste are introduced in Chapter 3.1. The demands on a methodology for the scenario of an automotive company is further elaborated in Chapter 3.2 based on the conclusions from Chapter 2.7.3.

After having established the demands, current solutions are brought to discussion in Chapter 3.23, and their fulfilment of the demands is discussed. The solutions derived from dissertation theses, published papers and practitioner literature are examined, finalising with a comparison and a research gap in Chapter 3.4.

3.1 Measuring Production Instability

Having introduced the concept of key performance indicators in Chapter 2.4.3, a general method of measuring production performance and waste with KPI according to industry standard is introduced.

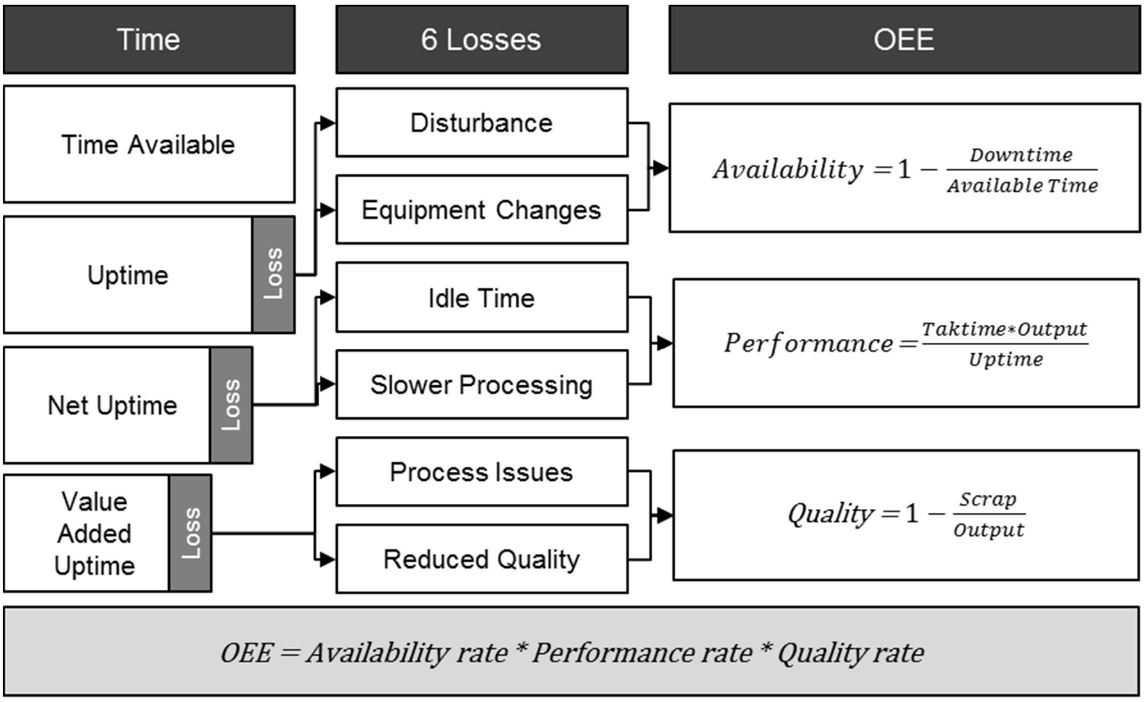

Figure 3-1 Calculation Overall Equipment Effectiveness according to NAKAJIMA[194]

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[194] Based on: Nakajima 1988, p. 25

Basic KPI can be calculated based on measurements taken, and linking them to a KPI system offers the possibility to get clear information on the actual state of operations. One of the most used KPI to evaluate the effectivity of a system is the Overall Equipment Effectiveness (OEE). The system is part of the Total Productive Maintenance (TPM) introduced by Toyota, and follows a calculation based upon six categories of loss as seen in Figure 3-1. Finally value added uptime is the relevant figure, as only during this time actual progress towards a final customer ready product is performed[195].

The six Categories defined are related to the machine and its outcome, and by introducing the OEE to a time dependence, a ramp-up overall equipment effectiveness can be discussed[196]. The stability and capability is then discussed by means of an statistical process control.

3.2 Requirements for Production Stability during Ramp-Up

According to the previous debate of principles in Chapter 2, a solution for the specifics of the automotive industry was described in chapter 2.7.3., as to establish a production control system in order to ensure the stability of a process. In total, amongst others, seven demands have been noticed which all need to be fulfilled for a method to be effective for the situation at hand. For a comprehensive discussion of state of the art literature, Chapters 3.2.1 to 3.2.7 specify the demands.

3.2.1 Low-Volume Focus

With the increase of variety and customisation of products and the decreasing lifecycle time, production facilities are economically forced to produce in a mixed model assembly line. With the introduction of every new product, the stability of the entire system is at risk, and production needs to be prepared to adapt quickly and controlled accordingly. As the trend is further accelerated by the introduction of Internet of Things (IoT) and the credo of “lot size one”, even currently mass producing industries are facing the issues existing in low volume production.

These changes bring their set of problems to the idea of production control. High customisation and highly deviating takt times between various derivates, lead to problems in balancing work packages and defining the optimal work content and sequence. Hence, the method depicted should be able to be flexible in adapting work contents, to balance the workload between workers[197].

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[195] Nakajima 1988, p. 25ff.

[196] Gartzen 2012, p. 68

[197] Heike et al. 2001, p. 107

3.2.2 Efficient Data Gathering

Literature describes often the issue of having too little data available to base decisions on[198]. This problem even intensifies, as low volume production is providing even less data. The methodology used therefore needs to base itself on the little data available from previous product launches, gather enough data to be able to act on its own, and finally provide the gathered data to future projects accurately in order to be implemented as a long-term solution. The integration of the method in a system therefore reveals the relevance of it being applicable during the entire ramp-up and not only specialised for one single phase.

3.2.3 Change Implementation

The output of a method to find process issues is in the most times a recommendation on how to change or improve a process. Therefore, it is essential that part of the method deals with the topic of change implementation and change management. By embedding the methodology in the base organisation, the interchange is steered by its systems accordingly, and communication is efficient across all projects and process partners.

3.2.4 Fast Feedback

With the limited time available, issues need to be recorded as fast as possible, for solutions to be tested as soon as possible. In the event that the new production is also launched on an existing line in a mixed model system, the importance of fast feedback increases even more. For this reason, to locate issues as quick as possible, a real time monitoring procedure must be set in place. With the immediate data stream, information is generated seconds after observed, and with the right knowledge, the process can be adapted quickly and effectively.

3.2.5 Practical Applicability

Methods developed in the confined spaces of academic research facilities often lack practical usability. The methods tend to be too complicated or complex and are thus not accepted by the industry. Other methods are too time consuming, or the administrative effort is too high, and associates do not even bother filling the system. The method therefore clearly needs to be easy to understand and use, and the benefit of the potential output must be clear from the beginning. The calculation of potential KPI must be relatable, and actions to solve potential issues clearly stated.

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[198] Cf. Chapter 2.5

3.2.6 Holistic Solution

With ever changing circumstances, the methodology used needs a certain degree of flexibility to adjust to special requirements of the company it is used by. Not only does it need adaptability from one company to another, but the comparison of different workstations or processes within the company must also be given. The methodology should inherently be used to describe both assembly and logistics behaviour, as these are consequently connected to one another.

Besides the different applications in one phase, the general targets of the ramp-up need to be observed. During early phases, the focus is on problem identification, while later phases emphasise on volume. This requirement leads to the conclusion that a certain degree of freedom must be existent to take measures.

By having different targets across the different phases of product introduction, the method needs to adapt to these changes as well. Nevertheless, the introduction of different methods during a ramp-up can result in the loss of knowledge, and undermine the entire activity. The validation of changes needs coherent data between phases, and loss can only be prevented if the method used is applicable throughout the entire ramp-up phase; issues and solutions directly show their effects in subsequent phases.

3.2.7 Anticipative Risk Management

Issues often faced during ramp-up are the sheer load of tasks to be performed upon. Any method in use should therefore give the user the knowledge where to focus. By capturing data from previous phases and projects, the method needs to provide the user with pre-emptive knowledge, and an estimation on how changes affect the result.

3.3 Assessment of Existing Approaches and Research Gap

Although some researchers have already developed solutions, general literature on instability during ramp-up and how to control it is scarce. Nevertheless, existing solutions need to be investigated on concerning the fulfilment of the requirements described before. The existing approaches are introduced one by one, and a summarisation is provided in Chapter 3.3.4

3.3.1 Dissertation Theses

Berg (2007)

In his work, BERG discusses various factors affecting the ramp up performance, and concludes on three main groups of factors, namely the ramp-up situation, design and preparation, and the ramp-up itself. It is concluded that there is no general approach available for a positive or negative outcome, but it is highly dependent on the actual circumstances. Further factors are built around the production system, the environment, and strategy of development projects. His findings are based on a comparative analysis of previous works by various authors, supplemented with the findings from two case studies. Providing a list of factors influencing the ramp-up performance, seven factors form the sub-groups of influences. Having analysed those factors, no solution on how to improve the system's performance is discussed. [199]

In preceding works, a performance measurement framework is introduced based on findings from literature, which conclude to compare the actual outcome of ramp-up with the set of objectives. Nonetheless, this work only remains as a suggestion on what needs to be established.[200] This is followed up by the introduction of a production management approach in a paper, which suggests the monitoring of production performance during ramp-up, but does not deliver the tools to do so.[201]

Gartzen (2012)

GARTZEN establishes the concept of discrete migration as a solution to deal with complexity and instability during a ramp up. He identifies two main drivers for complexity, namely product variety and product novelty. His approach is the correlation of this complexity with instability, and out of this, he resolves that in order to be stable, the complexity needs to be dealt with by the use of enablers. They function as a counter to the drivers and stability is established by usage of various enablers[202].

In order to deal with unexpected instability, he proposes a KPI system based on the concept of calculating loss. Fifteen base KPI are identified, which are condensed first to five "level 2" KPI, which can be further condensed to the "level 0" KPI "Overall Equipment Effectiveness". Grouping the losses into three categories; those being losses due to quality, performance and availability, the first two are calculated by means of comparing lost volume to total volume due to various implications, while availability calculation is based on time lost for use.[203]

The aspect of discrete migration is furthermore based on the fact, that in the initial status, all complexity enablers are needed. Once stability is reached by means of statistical process control, one by one the enablers are taken out of the system until the system is again in a state of instability. The production is then again stabilised, and once all enablers are omitted, ramp-up has finished.[204]

Meissner (2009)

MEISSNER'S approach is focusing on stabilising the logistics processes. The core of the hypothesis is that keeping the order of production strongly according to plan enables the

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[199] Berg 2007, p. 69ff.
[200] Berg 2007 Appendix I
[201] Berg 2007 Appendix II
[202] Gartzen 2012, p. 104ff.
[203] Gartzen 2012, p. 204ff.
[204] Gartzen 2012, p. 217ff.

logistics to adjust its processes accordingly and stabilise[205]. The method is split into four systems, the first being assessment followed up by evaluation, design and implementation.[206]

Firstly, he introduces several new KPI that are providing information on the product's position in context of the entire production schedule, its delay according to takt as well as deviations of work in progress.[207]

The evaluation system is an in depth analysis of value streams, providing the user with a transparency on the location where turbulences occur. Transforming the outcome subsequently into a model, gives transparency on influencing factors. Further steps in the method are the design of measures and their subsequent implementation, everything based on the premise that a stable production schedule is the solution to instability.[208]

Risse (2003)

Optimisation of the time-to-market in the automotive industry was the key goal of RISSE'S research. Concluding that the ramp-up is not achieving its goals due to various reasons, an approach based on logistics is the solution to achieve earlier and steeper ramp-up curves.

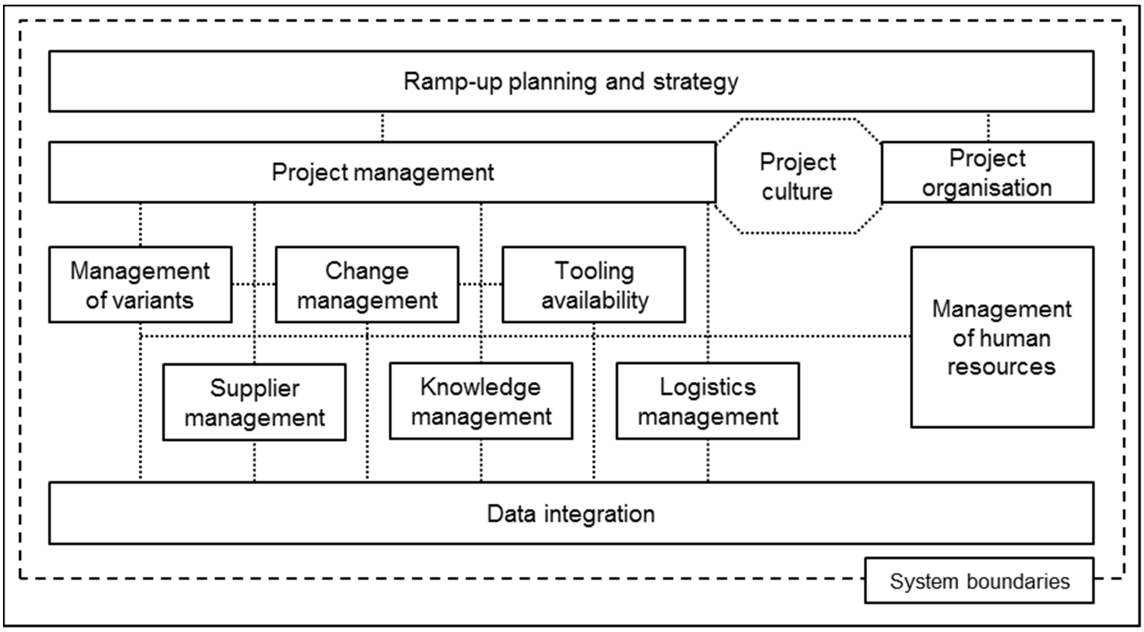

Figure 3-2 Modules of a logistics oriented ramp-up management[209]

RISSE offers a process oriented control approach, based on data gathered from previous ramp-ups. The method developed is based on two pillars, first defining the targets by

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[205] Meissner 2009, p. 49
[206] Meissner 2009, p. 67ff.
[207] Meissner 2009, p. 83ff.
[208] Meissner 2009, p. 111ff.
[209] Translated from German: Risse 2003, p. 264

means of mathematical approach, and then controlling the execution[210]. KPI used for measuring the level of logistical service are delivery time, on time delivery, delivery capacity, delivery flexibility, quality and transparency. The final proposal of using a balanced scorecard is not followed up by recommendations in case of instabilities.[211]

To achieve targets, a set of methods is provided, all of them changing or influencing the chosen ramp-up strategy. As one of the few authors, he describes the necessity to implement a proper change management system, to adapt to changes in the parts build list and derive proper launch control. The achieved results of this change management system are then transparency, fast feedback, standardising the change process, as well as ensuring the correct dress level of parts and usage of outdated parts if necessary.[212]

Furthermore, a system for efficient knowledge and problem management based on web databases is introduced. By combining all of these modules, a general management system for a logistics oriented ramp-up is defined, as seen in Figure 3-2.

Tuecks (2010)

TUECKS research concludes that in order to be successful, a control loop for the entire ramp-up is needed, based on the general concept of cybernetics, system theory and networking. The foundation of the loop is a modular approach, consisting of establishing a ramp-up model, a measurement module, a planning and decision module and an adjustment module, as seen in Figure 3-3.

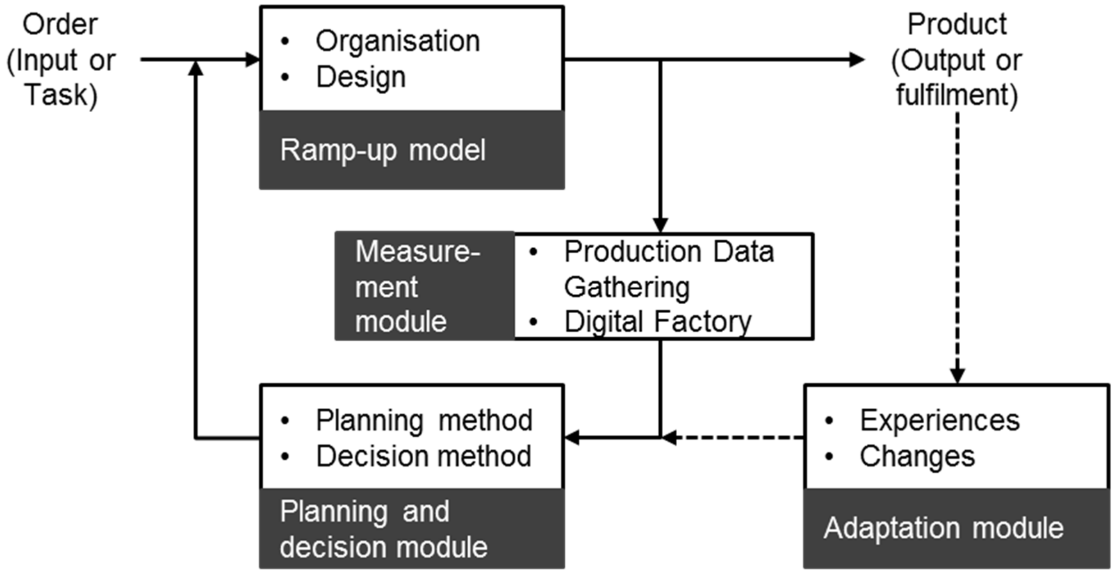

Figure 3-3 Production control loop developed by TUECKS[213]

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[210] Risse 2003, p. 167ff.
[211] Risse 2003, p. 167ff.
[212] Risse 2003, p. 220ff.
[213] Translated from German: Tücks 2010, p. 106

Based on empiric research, the ramp-up model is giving suggestions for targets and a modelling approach is provided by usage of the EXPRESS_G language. The model is further refined by introducing the other modules, with their interaction towards each other. Further elaborating the structure and systems of the models, the outcome of his work lacks the introduction of recommendations for immediate stabilisation.[214]

The planning and decision module has a problem solving approach at its core, starting with definition of targets. The target definition is needed to avoid conflict of interests once solutions are evaluated.[215] As such, all modules are further elaborated, and an extensive description of each based on EXPRESS_G is given. Using the digital factory as a means to improve data quality, Tuecks approach is a holistic method for production control.[216] The methodology remains blind to the determination of possible risks, and implementing necessary changes.

Zeugtraeger (1998)

ZEUGTRAEGER provides a holistic approach towards ramp-up management. He considers the commissioning of entire manufacturing sites, and adapts the general concept of project management onto the ramp-up. With changing targets throughout the ramp-up, he introduces the concept of quality steered ramp-up.[217]

Addressing change management by the concept of an organisational learning, driving the innovations and improvements of the venture. For advanced risk management, the usage of Project and Product-FMEA is advised. Furthermore, a method for analysing projects and hence transferring the knowledge to other projects is elaborated. Emphasis is on finding patterns in order to help manage the complexity of current projects, concluding that an appropriate IT-problem management system is needed.[218]

He does not deliver a method on how to measure or steer the production itself, apart from emphasising on the importance of learning and knowledge transfer.

3.3.2 Scientific Papers

Basse (2014)

By extending on the works of GARTZEN, BASSE defines four solution principles to increase ramp-up performance. The base theorem being that with adequate models, estimations on the future state can be given. With the combination of closed loop control and heuristics, the systems behaviour is then adjusted, and thus the complexity reduced. Building on the trade-off between planning accuracy and effort, establishing tolerances

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[214] Tücks 2010, p. 108ff.
[215] Tücks 2010, p. 110ff.
[216] Tücks 2010, p. 119ff.
[217] Zeugtrager 1998, p. 81ff.
[218] Zeugtrager 1998, p. 86ff.

provides the organisation with more knowledge on the consequences of deviations. In the end, an approach of pattern building and self-optimisation is introduced, the first being to help understand results without knowing the causes and effects, and the latter to enable control loops.[219]

Cube (2014)

Addressing the need for an applicability, CUBE'S approach combines risk management and day-to-day operations. The developed methodology starts with risk identification, grouping potential risks into two groups "product and process flaws" and "documentation flaw", with the potential of including sub-groups. With a subsequent risk assessment by means of historic data or Monte Carlo Simulation the risks are then quantified, and an evaluation of the biggest risks is performed. Afterwards, a risk report is prepared, and the focused treatment of risks starts. Providing various parameters to be calculated in order to determine the risk potential, concluding in further research needed on the topic to quantify the effort required.[220]

Gleich (2012)

GLEICH describes a method on how to handle the complexity and uncertainty in ramp-up situation by a "3-cycle" model. The paper strongly focuses on the topic of aircraft manufacturing and makes a clear distinction towards the automotive industry, due to longer product life cycles of airplanes and the high customisation of products. His three cycles are management of disturbances, change and maturity gate. The main concern is the impact of unintended disturbances, and thus he concludes that a balance of "production-protection" needs to be installed, in order neither go bankrupt or into catastrophe.[221]

Herrmann (2009)

The generic PDCA[222] circle is the base of HERRMANN'S approach. Seeing the time as the main driver during a ramp-up, he introduces a new KPI, the ramp-up failure rate (RTR) as a measurement tool for problems. The measurement is performed via a database, and associates can quickly check if issues with product quality exist. The method is to calculate the ratio of failed examinations against the total amount of examinations. This ratio eliminates the impact of a ramp-up product's issues being overshadowed by the amount of series products.[223]

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[219] Basse et al. 2014

[220] Cube, Schmitt 2014

[221] Gleich et al. 2012

[222] Plan-Do-Check-Act is a generic cycle approach in quality management to improve process and product quality

[223] Herrmann 2009

3.3.3 General Literature

A lot of research focused on generic ramp-up management and discussion of strategies. Although some offer insight on the problems encountered during these phases[224], few offer direct solutions for stabilisation the production and processes.

Bomm (1992)

BOMM establishes base performance indicators for control of investing in production systems. Grouping the targets and measurements into six, he provides KPI for evaluation. By developing a target- and KPI-system, he gives a holistic approach to determine the performance of entire production facilities. Although his work is mainly focusing on economics, the base KPI used for calculating assembly and logistics performance are well suited as a foundation to build upon.[225]

Gustmann (1988)

The approach provided by GUSTMANN is an overall approach for ramp-up management. Defining different types of ramp-up, the research focused on describing the behaviour of a ramp-up. Identifying technical-technological and workforce associated sources of disturbances, the resulting consequences are always described as having effect on assembly time, throughput time, and resources usage[226].

By identifying influencing factors, and directly correlating them to various characteristics of ramp-up management, a first idea of anticipative problems is shown. GUSTMANN'S methodology describes the analysis of ramp-up behaviour as a means to influence future product launches[227]. He follows earlier research giving indication that progress follows some kind of learning curve, and describes the anticipation and estimation of a ramp-up's behaviour as mathematical functions following a basic power function. Provided with a table on possible influence factors and calculating them by comparing the actual recorded data from previous ramp-ups, he defines a ramp-up coefficient, which is a representation of the organisations increase in process ability. He correlates the functions with six main factors that affect the future state, such as degree of novelty, complexity and complicity.

The methodology is following a six-step approach to plan the ramp-up, and the result being either the estimated duration of the ramp-up, or the volume produced in the end of the ramp up. For determining each coefficient, further parameters are introduced.[228]

The performance measuring system introduced focuses solely on the associate training. The author later provides the reader with recommendations on how to support the worker

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[224] Amongst others: Schuh 2008, Kuhn 2002, Slamanig 2011
[225] Bomm 1992, p. 85
[226] Gustmann et al. 1989, p. 31ff.
[227] Gustmann et al. 1989, p. 57ff.
[228] Gustmann et al. 1989, p. 82ff.

in acquiring new knowledge. The application or measurement in real time is not discussed at all.

3.3.4 Comparison of Existing Approaches and Research Gap Gap

Having derived the various criteria for an effective production control system in Chapter 3.1, and the subsequent discussion of existing research in the field of ramp-up and production control, a comparison of the different approaches is needed. This comparison is summarised in Figure 3-4. A filled circle depicts that the requirement is fulfilled within the specified literature, while an empty circle indicates a low or non-existent degree of fulfilment. If the requirement is discussed at least partially, a filled semicircle is used.

			Requirements on Methodology						
			Low-Volume Focus	Efficient Data Gathering	Change Implementation	Fast Feedback	Practical Applicability	Holistic Solution	Anticipative Risk Management
Discussed Approaches	Dissertation Theses	Berg	◐	○	○	○	◐	○	●
		Gartzen	○	●	○	◐	○	●	◐
		Meissner	○	◐	○	◐	●	○	○
		Risse	○	◐	●	○	◐	◐	○
		Tuecks	○	●	○	◐	○	●	○
		Zeugtraeger	○	●	◐	○	○	◐	◐
	Scientific Papers	Basse	◐	○	○	○	◐	●	○
		Cube	○	◐	○	○	◐	○	●
		Gleich	●	○	◐	○	●	◐	◐
		Herrmann	○	●	◐	●	○	○	◐
	Gen. Lit.	Bomm	○	●	◐	○	●	○	○
		Gustmann	◐	○	○	○	◐	◐	●

Degree of consideration: ● High ◐ Middle ○ Low

Figure 3-4 Comparison of reviewed literature

None of the discussed approaches could fully fulfil all demands raised towards the methodology. Especially the implementation of changes was regarded not as essential. Only RISSE discussed thoroughly how changes should be implemented. Although nearly all requirements regarding the ramp-up management are given, a lack of production control is obvious. Some of the researchers focused only on specific phases, most where targeting the scale-up phase after start of production. Although initially stated, most of the research would have a practical applicability. The lack of seeing these approaches in the industry might result from the complexity of the instructions. Nearly all authors understood the problem of little data available, with some having extensive descriptions on sources of data. However, even the most sophisticated approaches were not suitable for a low-volume context. Except for GLEICH, who focused on the aero industry, only high volume or mass production was defined as the field of research. Basic risk assessment methods are provided by both GUSTMANN and ZEUGTRAEGER, but only CUBE and BERG provide detailed instructions in “how to”. Finally, nearly all researchers neglected real time control of the production, except for HERRMANN whose method was focusing heavily on this, but lacks practicality and low-volume applicability.

With the analysis provided in this chapter, it can be concluded that not a single approach currently fulfils all requirements. Therefore, the need for a new methodology is given. Chapters 4 gives a short outline of the method, while Chapter 5 gives an extensive elaboration of the developed methodology to close the research gap and ensure process stability.

4 Methodology for Process Stabilisation

The decrease of product lifecycles and the increase in derivatives drives companies to increase the frequency of ramp-ups. A delayed problem identification usually results in high unplanned costs. Losing customers due to poor quality or late delivery does not only affect newly introduced products, but also those from series processes. The theoretical basics discussed in Chapter 2 helped identify specific criteria. With these, different approaches to reducing ramp-up instabilities were analysed and compared in Chapter 3. With following evaluation, lead to conclude that there was a research gap, and a demand new approach was necessary.

The following chapter is a general introduction to the newly developed methodology, with Chapter 4.1 complementing the demands, followed up by the introduction of the main research hypotheses in Chapter 4.2. The last Chapter 4.3 outlines the resulting methodology to use for stabilisation.

4.1 Demands on Methodology

Based on the research field introduced in Chapter 2, seven base demands towards a successful methodology were defined in Chapter 3.1. Adding to these requirements, and considering the research gap outlined in Chapter 3.3.4, further demands to the methodology itself are deduced, required for a practical implementation in an industrial environment. The demands are further divided into formal demands (Chapter 4.1.1) and demands regarding the content (Chapter 4.1.2). These are mainly used to clarify the requirements towards a methodology for ensuring production stability.

4.1.1 Formal Demands

The formal demands mainly relate to the outcome of this thesis, and hence to provide a basic understanding of the term methodology. According to the Oxford dictionary, a method is "*a particular procedure for accomplishing or approaching something, especially a systematic or established one*"[229]. The summation or chain of methods then forms a methodology. Defined in the same way as the above as "*a system of methods used in a particular area of study or activity*"[230]. According to these sources, a methodology therefore needs a specific set of methods, chosen to contribute to the solution of a defined problem. Nonetheless, a developed methodology is not a stand-alone solution, and other aspects such as expert knowledge and experience contribute to the success in finding a solution[231].

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[229] Oxford University Press 2016, Keyword: Method

[230] Oxford University Press 2016, Keyword: Methodology

[231] Haberfellner, Daenzer 1997, XIX

4.1.2 Content Specific Demands

The investigation of state of the art approaches in Chapter 3.3 focused on the potential approaches from ramp-up management and production control. The concepts and methods identified in the preceding discussion may contribute to a suitable methodology, but three main aspects remain undiscussed. One of them is the applicability in a low-volume context, taking into consideration the specifics defined in Chapter 2.6.2. As management is facing many issues at the same time, an advanced risk assessment should be provided to enable focusing on the main issues, and correct change implementation needs to be highlighted.

The approach of process control chosen by previous research often had the output volume as a performance indicator in order to deduce how much time is lost due to various different aspects. In the context of low-volume production, this is not providing the same level of detail, since numbers are too low. Therefore, a methodology to be applied in said context needs to adhere to these circumstances accordingly.

As described in Chapter 2.5.2, many factors influence a successful ramp-up. With having to focus on many fields at the same time, a methodology should include a possibility to define the main issues in advance. Also with the ramp-up being generally a state of low data availability and unclear processes, the methods set into place should be able to extrapolate as accurately as possible from only little amounts of data available.

The third aspect of an effective ramp-up management and stabilisation tool is the change management. Since the organisation is in a state of constant change anyhow during this phase, there is no problem in dismissing some of the eight steps towards change[232]. Nevertheless, installing a proper process that is then followed by all parties involved is necessary.

4.2 Research Hypotheses

The following chapters discuss the main scientific contribution of this thesis, and provide the basis for the methodology developed. The main hypotheses target at answering the three research questions introduced in the first chapter.

4.2.1 Advanced Identification of Issues

As established in earlier chapters, the takt time and throughput time are key factors to be stabilised, in order to have a stable production system. Thus, defining potential deviations and takt time exceedances is useful for mitigating problems upfront. As the actual takt can highly deviate from the expected takt time calculated by time measurement methods, full production control requires upfront estimation of deviations.

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[232] Cf. Chapter 2.5.5

The advantage of early problem solving is an established fact, with frontloading development and prototyping being efficient methods for reducing project costs in the long run[233]. Transferring this idea to production control, comparison of changes per workstation (WS) delivers possible risks. After the start of production, a thorough observation and notification of problems by the worker himself benefits the search for problems. Encouraging and training the workforce to report every issue even though the impact on the production seems minimal is crucial for achieving a holistic picture of problems.

The hypotheses is to use these recorded problems to identify problematic workstations after having launched only a few products, as the deviation from a set takt time seems to correlate with the amount of problems. Additionally, the occurrence of problems correlates with the novelty of the product and process, leading to the suggestion of analysing the degree of novelty to identify potential risks and shift focus towards these.

Data investigation of two build phases has shown a linear correlation of 70% between problems reported and time measured, increasing to 85% by filtering non-assembly relevant and “one off” issues[234]. In field experience suggests, that decoupling the reporting from the administrative task of problem recording increases the amount of raised issues. A high increase of reported incidents may overwhelm standardised problem management systems, resulting in the need for a simplified solving process for minor problems.

4.2.2 Real Time Process Control

During production of a prototype, companies can choose to produce on a separate line or on a mixed model line together with other products. While in the first case production instability during ramp-up has little to no impact on a series process, producing on a mixed model line can lead to disturbances in series production.

Two major impacting factors observed during research in the field as well as in literature were parts availability and out-of-process assembly. To keep these issues from spreading throughout the factory, a containment process needs establishing. The introduction of real time process control and a fast response system show promising results to minimise the impact of missing parts or immature assembly steps.

As mentioned, parts availability is deemed the main concern for stable production systems. With the introduction of a quick response go-to-point, processes are stream lined and emergency picks reduced. Most parts reported missing at point of fit were actually set-up for a different station or released late, resulting in the described errors. With the introduction of more variants to the assembly line, problems are increasing, and

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[233] Thomke 2000, p. 128

[234] These values apply to a specific assembly system. Depending on the system at hand, different observations might be useful.

stable data management is unquestionable. Nevertheless, a streamlined process reduces disturbances within the system, relieving the pressure from an already highly intense system.

By shifting work content between workers and introducing floaters, takt times are kept in tolerance boundaries. Although these shifts have shown to be of effect, overuse should be limited, as the experience increase of the actual worker suffers, and underlying problems might stay hidden. Resulting from that, a detailed documentation of measures introduced is a pre-requisite to keep the outcome of the build phase on track with the targets.

4.2.3 Time based KPI System

Unavailability and inaccuracy of data is a permanent state during a production ramp-up. In contrast to that, production control demands for known input and output parameters. This situation is no satisfying and asks for improvement. As discussed in previous chapters, key performance indicators can provide information in a condensed way, letting management take decisions quickly. Literature on KPI during ramp-up is rare, and if available, seldom applicable in low volume production. Hence, development of a detailed KPI system is relevant for future ramp-ups.

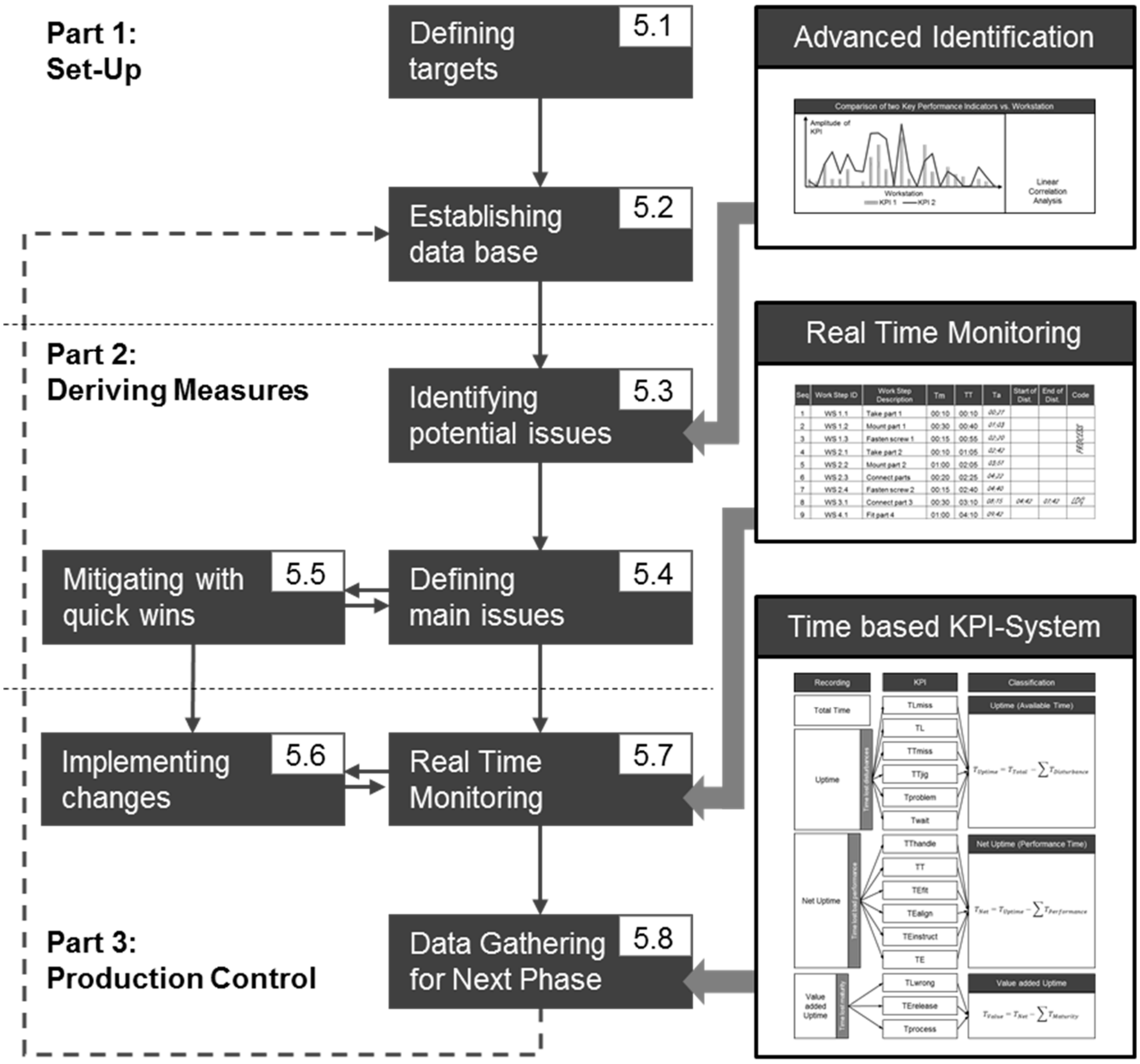
The research hypotheses now is that basing a system on active time measurement against a theoretically determined time leads to detailed measurement of loss, which can be put into perspective easily. The previously established calculation of losses by means of volume comparison is not applicable if the daily production is low. This deficiency is solved by measuring the actual time of manufacture for indicating losses and inconsistencies.

4.3 Overview of the Methodology

The base idea of real time process control is the lead enabler to achieve the primary goal of production stability, and thus forms the base of the methodology. A brief description of the developed process is given in this chapter, with a thorough elaboration given throughout Chapter 5. The method is according to the previously described research gap, the given demands and the research hypotheses at hand. Figure 4-1 shows the components it consists of with the respective subchapters for the elaboration in Chapter 5.

The developed method consists of eight steps, following the general approach of acquiring knowledge from data according to Chapter 2.4.2. The overall approach is a flow for one build phase, repeating its process steps for every following phase until achieving a stable series production. The method is split into three parts for an easier understanding.

At first, the set-up is essential for understanding the system and increasing its efficiency. By defining the targets and understanding the goals of the specific phase, the focus can be set accordingly. Setting a target for implementing the method enables choosing the correct performance indicators for the tasks ahead. Chapter 5.1 extends on this topic and gives suggestions on possible targets. By identifying problems as soon as possible, actions can be set and tested at an earlier time in the product lifecycle. Potential issues need to be recorded, and a solid database is established (Chapter 5.2).



Seq	Work Step ID	Work Step Description	Tm	TT	Ta	Start of Dist.	End of Dist.	Code
1	WS 1.1	Take part 1	00:10	00:10	00:27			
2	WS 1.2	Mount part 1	00:30	00:40	01:03			PROCESS
3	WS 1.3	Fasten screw 1	00:15	00:55	02:20			
4	WS 2.1	Take part 2	00:10	01:05	02:42			
5	WS 2.2	Mount part 2	01:00	02:05	03:57			
6	WS 2.3	Connect parts	00:20	02:25	04:22			
7	WS 2.4	Fasten screw 2	00:15	02:40	04:40			
8	WS 3.1	Connect part 3	00:30	03:10	08:15	04:42	07:42	LOG
9	WS 4.1	Fit part 4	01:00	04:10	09:42			

Figure 4-1 Overview of the Methodology

Upon finishing initial data investigation, data is refined and transformed into information. Comparing the target and the as-is state with detailed data available, is key to understanding the initial status, and provides first ideas for improvement. To optimise the data outcome of the build phase, thorough analysis is needed (Chapter 5.3). Provided with this starting point data and a comprehensive analysis, the user is enabled to undertake first adjustments, setting the foundation for the future.

After noting issues and correlating them with parameters set up as targets, a Pareto analysis reveals the main ones that need to be resolved (Chapter 5.4). Every target defined requires a measurable and possible to influence indicator, for instance the takt time and product quality. With emphasis on the level of detail, this data is necessary for mitigating issues with quick wins where possible and useful (Chapter 5.5). The mitigation can have various forms depending on the issues underlying, from standard application, like decoupling of pre-assemblies to more flexible approaches of work content adjustment or station balancing. During these adjustments, data is gathered and fed back to the main issues, creating a prognosis for the next period.

Implementing changes during the following phase needs proper change management, with regular communication with all involved parties (Chapter 5.6). These changes can range from slight differences in assembly sequence, to extensive changes such as decoupling of process steps or delivery concepts. None the less, the effectivity of all these changes has not been confirmed and permanent real time monitoring needs to be established. By checking the current progression of the assembly against a theoretical progress, observed deviations from the target are resolved by immediate countermeasures (Chapter 5.7). These measures should not produce further instability, hence previous acceptance by the staff and a standardised process is demanded. With a strict protocol and data gathering, the effectiveness of certain measures is confirmed, and if conditions are met, these changes are implemented for the following production phases or even transformed into series process. This is the final step for having acquired knowledge.

During the build phase at hand, additional data is gathered and the process flow starts from the beginning, in order to stabilise the next production step and increase the process knowledge (Chapter 5.8), closing the ramp-up control loop. With the concept of discrete migration in use, the targets for the next production steps are expected to change, and necessity for additional KPI might emerge.

5 Elaboration

Focusing on the elaboration of the methodology for process stability control presented in Chapter 4, the steps are elaborated in detail in the following sub-chapters. The first two chapters, chapters 5.1 and 5.2 provide a general suggestion of targets for a stable process, followed up by data sources and measurements on how to discuss their achievement based on availability. The second part introduces the analysis of potential issues, the definition of the main issues, and finalising with a strategy to mitigate these risks, examined in chapters 5.3 through to 5.5. Chapters 5.6 and 5.7 point out the last components of production control, change implementation and real time control. Closing the loop and feedback of data to acquire knowledge is the topic of Chapter 5.8, the increase of process knowledge. Afterwards, a practical application of the methodology provided in Chapter 6 clarifies remaining questions.

5.1 Defining Targets

As introduced in Chapter 4, the developed method follows a target oriented management approach. Introducing the production control process in Chapter 2.4.1, by comparing target and actual values, the paramount need for defining targets is evident. As the main targets vary throughout the ramp-up, the criteria chosen need to be adapted accordingly. The following two chapters deliver potential targets for the different phases with special emphasis on production and logistics. Chapter 5.1.3 provides an in depth analysis of every target.

5.1.1 Targets of Assembly

The primary target of assembly is to produce a product under stable input and output conditions, as described in Chapter 2.2.2, and ramp-up is the transition phase to get there. The initial step of ramp-up is getting an understanding for the product and the new technologies. The first presentation of the product outside of engineering models and prototypes, built by the project team, is the core of this phase. According to ZEUGTRAEGER[235] (Quality Phase) and SCHUH[236] (Pre-series) the prevalent targets are:

- Identification of problems
- Process try-out
- Workforce qualification

According to the same sources, the second phase is targeting high volume and integrating the product into the main production facilities. The location is already the site

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[235] Zeugtrager 1998, p. 81ff.
[236] Schuh et al. 2008, p. 1ff.

of series production, and the targets added to the previously defined ones are accordingly:

- Volume
- Process improvement
- Validation of process changes
- Product quality

The possibility of transferring the production onto a mixed model line results in the **stability of series production** being a secondary target for the project, but a primary one for the business.

The third phase already produces products for customers. As a conclusion, **meeting series condition** is the primary target of production.

5.1.2 Targets of Logistics

Logistics as a process partner of production plays an essential role in assembly's ability to achieve its targets. Meeting logistics' targets is therefore an integral goal of the project team, and parts availability being the primary one.

During the earliest phase of ramp-up, logistics is developing delivery concepts and material flow routes. As multinational companies have a centralised engineering department, logistics is divided between multiple departments. The central planning department is usually in the lead for providing pre-series supply, while the factory's department organises later phases[237]. The targets in the first phase are hence **developing supply networks**.

After introducing the product to the main production site, the targets shift towards a customer orientation for assembly. Furthermore, securing the delivery of parts to the line, and thus enabling the assembly to achieve their targets of volume and process workforce qualification should be in focus.

- Validation of material flow concepts
- Validation of packaging concepts

As with assembly, by focusing on the introduction of new products the series process may not suffer, hence **stability of the series production** and **meeting series condition** are the targets towards the end of the ramp-up.

5.1.3 Description of Targets

For further discussion of the methodology, a short description of the targets defined in chapters 5.1.1 and 5.1.2, summed up in Table 5-1, is given in the following. The targets as shown are marked as major or minor targets. The split according to the build phase

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[237] Schuh et al. 2008, p. 144ff.

only forms a suggestion derived from the previous chapters, as targets may differ from one project to another. Essentially, all targets introduced are valid for build phases later in time, but it expectations are they stay at least at the level they were at the end of the previous phase they need no close monitoring.

Ramp-Up Targets by Technology and Phase

Target		Phase	Quality Phase	Volume Phase	Scale-Up
Targets of Assembly	Stable Production	Identification of problems	● A	◐ A	◐ A
		Achieve process maturity	● A	● A	◐ A
		Qualify associates & employees	● A	● A	◐ A
		Throughput time	○	● A	● A
		Achieve product maturity	◐ A	● A	● A
Targets of Logistics	Parts Availability	Develop supplier network	● L	◐ L	◐ L
		Validation of material flow concepts	○	● L	◐ L
		Validation of packaging concepts	○	◐ L	● L
Overall targets	Stability of series production		○	◐ O	◐ O
	Meeting series condition		○	◐ O	● O

○ No Target for build phase	◐ Minor Target for build phase	● Major Target for build phase
Ⓐ Target of assembly	Ⓛ Target of logistics	Ⓞ Target of overall organisation

Table 5-1 Overview ramp-up targets by technology and phase[238]

Targets of Assembly

The main target of the entire ramp-up is for the assembly system to adapt to a new product[239], and assemble products that do not vary too much in their specification. To achieve this, the organisation must fulfil every target throughout the phases needs. Only then achieves production a stable state[240].

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[238] Phases according to Zeugträger, 1998 and Schuh, 2008

[239] Berg 2007, p. 1ff.

[240] Gartzen 2012, p. 73ff.

Identification of Problems

With the introduction of front loading, the idea of early error and failure recognition is the primary goal of the early build phases. The focus should be on problems that are relevant to the actual physical assembly of parts. The question at hand is whether associates can assemble the product as it is, or if modifications to tools are still necessary. Another area of interest is the maturity of jigs and fixtures used for assembly. Here the focus should lie on the general concept. Surface quality of parts and ergonomically designed tools should not be relevant in early phases, as parts quality focuses on them later in time[241].

Achieve process maturity

As the introduction of new products often comes along with the usage of new technologies and new sub-components, early builds deliver first hands-on experience for them[242]. Investigating these new process steps as soon as possible can result in fast feedback to engineers, which enables quick adaptation of crucial changes. The target for new complex processes should be to include as many repetitions of the process steps as economically sensible, as these deliver the possibility for detailed error investigation and higher workforce qualification. The more complex a production sequence is, the more time should an organisation spend trying it out.

Issues found in previous periods of assembly lead to the introduction of solutions in subsequent phases. These changes need to be validated and if needed redeveloped. This phase of iteration demands for flexibility and accurate planning, as try-out is a hindrance to volume increase. Process changes are affecting the stability in a negatively, hence close observation of their implementation is obligatory. The target for process changes is therefore to be effective in their specific context.

With the introduction of new parts to the production facility, logistics can test possible changes to the material flow during the pre-series and null-series. Although not a core target of the project, the factory can use these phases of change for implementing and validating them. Goals are the same as for process changes, resulting in a monetary or similar benefit, and monitored afterwards similar to the process change. For non-monetary changes, comparison of stability and capability values before and after the change confirms positive effects.

Qualify associates & employees

The first confrontation of the ramp-up associates with the new product occurs in pre-series builds. Usually they are still part of a special project team[243]. Their understanding of the specialties, quirks and issues with it are relevant for future progress. As they are

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[241] Tools are not grained for instance before the geometric shape of the part is confirmed
[242] Cf. Chapter 2.5.1
[243] Tücks 2010, p. 27ff.

the people to multiply the knowledge to the regular staff, their training is essential for future progress.

As it is the project team’s duty to train the associates of the series process afterwards, this is a target throughout the entire ramp-up. Only in the end, once the release to customer order has started, should training be less of an importance. A specific target value cannot be provided in the context of this thesis, but it is obvious that for series condition nearly all associates need to be qualified for their task[244].

Throughput time

With the transition from early quality orientation towards production start, the focus shifts from problem finding to volume increase. By expecting the product maturity to have reached an adequate level for a smooth process flow, volume and throughput become the predominant goal. The numbers demanded should be according to the phase it is in, and during later pre-series builds approaching the numbers given by the expected demand during series.

Achieve product maturity

Although a target of the parts quality departments, or their respective counterparts in supplier management, having an increase in product maturity is also a target for assembly. By having parts out of robust processes, the tolerances under which production is assembling the parts decrease, achieving an improvement in takt time and ergonomics. In addition, an increase in quality leads to reducing rework, one of the seven wastes of lean management. Therefore, a quality monitoring of parts delivered to assembly should be set-up, to provide evidence on issues unrecognised before. The target here should narrow down to zero defects per part.

Targets of Logistics

Throughout all of the ramp-up, the main target of logistics is to have all parts ready for assembly. Ensuring the availability before the actual production starts is the trivial goal. Nonetheless, this security may not lead to omitting all standard processes. Integrating the new parts into the standard process is key to ensuring a stable system. Target value is 100% of the needed parts are available in the correct quantity and quality at the launch of a new phase

Develop supplier network

Logistics first confrontation with products is in the early phase, when initially introducing new suppliers. As early process partners, logistics goal is enabling the entire supply chain network’s transportation, and plan external logistics in consequence. Storage concepts and in and outbound traffic need according adjustments. As such, measuring

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[244] A qualification of 100% is unrealistic, as through fluctuation of workers qualification levels change as well

the achievement of the target directly through KPI is futile, but nonetheless the goal should be to have an agreement with all parties.

Validation material flow concepts

With the addition of new parts to the factory, the actual presentation of parts to the assembly workers requires detailed planning. Last minute changes in parts specification, or unknown issues due to material properties, result in changes, which need to be steered accordingly. In addition, the delivery to the workstation is subject to changes due to assembly processes changing their sequence, which need to be adapted by logistics. The material flow routes need verification for the series process, and adapted where issues occur. Those material flow process themselves demand stabilisation in terms of parts quality and availability. The target should be achieving a 100% validation of delivery and material flow concepts latest by the introduction of the product to the factory.

Validation of packaging concepts

Packaging of parts is one of the contributors to good product quality, as wrongly packaged parts are prone to damaging, leading to a decrease in customer satisfaction. Dependent on the agreement between the business and its supplier, developing a packaging concept is task of one or the other[245].

During ramp-up, the entire system is under pressure, and so is the storage facility. For proactive storage usage planning, packaging concepts need a predefinition in early phases. Although the volume of delivered parts is below the usual threshold to use the series packaging, giving restrictions on packaging sizes allows logistics to get storage demand and layout planning done.

The importance of the actual packaging concept is irrelevant in early phases, but every part approved for series production should have a defined packaging concept. The validation usually takes place during the late phases, as only then is series packaging actually used. However, some tests for critical parts should be included in early phases to use the benefit of early problem identification. Incorporating a zero complaint target results in saving last minute changes towards the supplier, and is therefore the go-to strategy.

Overall Targets

The last to targets specified are required to be fulfilled by the organisation as a whole. Assembly and Logistics as well as all other process partners in the factory need to ensure the stability of the current production, as well as the overall target of a ramp-up, meeting series conditions in the end.

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[245] Schuh et al. 2008, p. 144ff.

Stability of series production

After the introduction of the new product to a facility with an existing product, the focus shifts from the first to the latter. Nonetheless, the still occurring series production should not suffer too much of an impact, as it is still producing for customers. As a result, the ramp-up project is obligated to ensure that series production meets its targets, with monitoring being according to series standards.

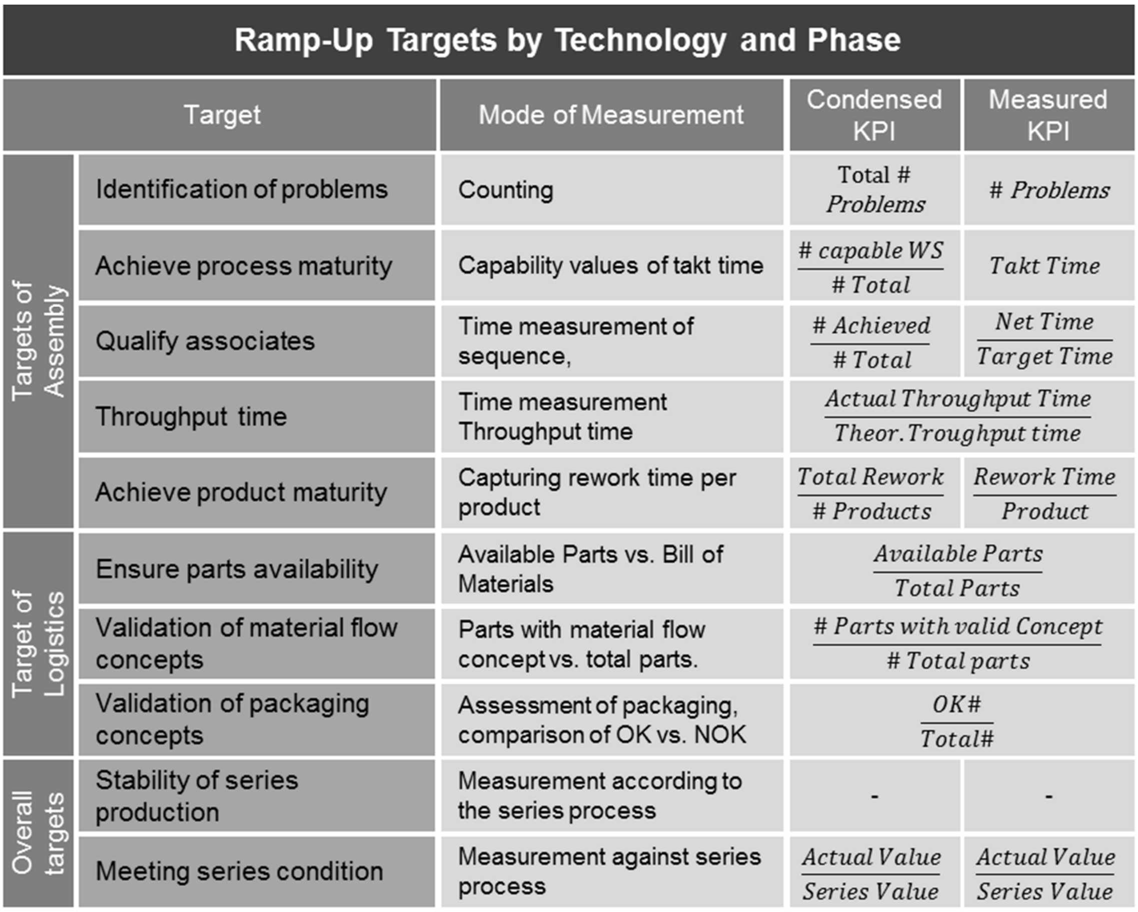
Meeting series condition

As the final target of every ramp-up project is an orderly handover to the factory and series support, meeting series condition is the final target of the production ramp-up. The project team withdraws, and the future responsibilities are only with the factory staff. To achieve this target condition by the project team, meeting all previous targets is required.

5.2 Establishing a Data Base

After defining the targets, the management of these comes into interest of the responsible actors. Despite having actual targets defined, many companies fail to set-up a system to measure the status accurately, thus having problems to look into the future state. This chapter provides an overview on how to measure the targets defined in Chapter 5.1, portrayed by a first overview in Table 5-2.

All previously defined targets are given their transformation into Key Performance Indicators, either being absolute or relative numbers. The table shows additionally the modes of measurement and the calculation of relating KPI, which are usually available in all production facilities without increased effort for investigation. The modes of measurement are introduced by the order of targets in the table. Linking the measurement to a workstation and to process steps is also necessary for future investigation and pre-emptive analysis, thus a system solution should include these aspects to handle the mass of data. As KPI have the ability to be broken down to every single workstation, the entire production is ready once all processes have reached their goals.



Ramp-Up Targets by Technology and Phase				
Target		Mode of Measurement	Condensed KPI	Measured KPI
Targets of Assembly	Identification of problems	Counting	$Total\ \#\ Problems$	$\#\ Problems$
	Achieve process maturity	Capability values of takt time	$\frac{\#\ capable\ WS}{\#\ Total}$	$Takt\ Time$
	Qualify associates	Time measurement of sequence,	$\frac{\#\ Achieved}{\#\ Total}$	$\frac{Net\ Time}{Target\ Time}$
	Throughput time	Time measurement Throughput time	$\frac{Actual\ Throughput\ Time}{Theor.Troughput\ time}$	
	Achieve product maturity	Capturing rework time per product	$\frac{Total\ Rework}{\#\ Products}$	$\frac{Rework\ Time}{Product}$
Target of Logistics	Ensure parts availability	Available Parts vs. Bill of Materials	$\frac{Available\ Parts}{Total\ Parts}$	
	Validation of material flow concepts	Parts with material flow concept vs. total parts.	$\frac{\#\ Parts\ with\ valid\ Concept}{\#\ Total\ parts}$	
	Validation of packaging concepts	Assessment of packaging, comparison of OK vs. NOK	$\frac{OK\#}{Total\#}$	
Overall targets	Stability of series production	Measurement according to the series process	-	-
	Meeting series condition	Measurement against series process	$\frac{Actual\ Value}{Series\ Value}$	$\frac{Actual\ Value}{Series\ Value}$

Table 5-2 Modes of measurement for initial ramp-up targets

Identification of problems

The measurement of problems identified is as simple as critical. Recording all issues that come up gives an approximate overview on the maturity of the product. Counting the sheer number of issues provides an estimation on the workload for departments. Using the current system in place at the plant is the preferred way of documentation. The high number of issues results in a temporary overflow of problem management capacity, but it is essential to record to the highest possible detail, in order to get best results towards maturity.

Achieve process maturity

As implementation of new products often implies introducing new technologies, process try-outs under close investigation should be part of early ramp-up phases. The definition of a mature process was defined in Chapter 2.3 as a state, where the input and output parameter are not changing significantly, hence being in a stable state. Therefore, the target of a mature process is achieved, once its parameters are not deviating by a lot anymore. The go-to parameter in this case is the takt time, or if the level of detail increases the sequence time. If its values are in the limits of system capability, the maturity of the process is proven.

Extending on the proving of capability, in order to verify the impact of the problem a detailed analysis of potential process improvement needs undertaking. The change is validated according to the reason it was implemented for, e.g. measuring saved time if that was the reason.

Qualify associates

The training of the associates is crucial for their knowledge of the product, and analysing and implementing changes. A highly qualified workforce is hence an enabler for a complex ramp-up, resulting in the need of monitoring their performance. The suggested measurement system is a work time oriented approach, with measuring the time needed to perform an action against a time derived from a time study. The sequences are then rated as OK (if the time is accurate enough) or NOK (if the time is exceeding too much). The overall work content is then displayed, and a KPI is calculated as an "*OK to overall*" ratio.

Throughput time

As it is the inverse of the takt time, the throughput time is often measured easily by summing up the takt times. The issues with low volume production are the long takt times and reduced production numbers in test phases, resulting in assembly times beyond regular shift patterns, sometime taking several days. This leads to the need of introducing the theoretical throughput time as a measurement tool. By calculating the time it needs to be built, a theoretical maximum volume per day can then be calculated, which is then matched against the targeted throughput time. The theoretical throughput time can be calculated as the product of number of workstations multiplied with the target takt time.

While the usual calculation of throughput time is to compare entry and exit times, the ramp-up has its specialities. Due to out-of-process actions like problem investigation, training and extensive rework on line, the measured takt time increases. In contrast to that, the actual time it takes to assemble the product is essential, and support processes can be ignored for stability validation. In consequence, the actual throughput time should be calculated by summation of all takt times. This calculation has also the benefit of increasing the motivation of the associates to achieve target times, and high takt times are an indicator for underlying issues.

Achieve product maturity

Parts quality monitoring is usually part of the process already, and performed at the supplier. Nevertheless, problems in product quality can have impacts on the process itself. These issues can sometimes not be solved on the assembly time, and need additional rework after the end of line. Adding the monitoring of rework times to the actual investigation, meaning that monitoring the rework times per product is a valid indicator to prove the product's maturity. To clarify, these issues are only those not caused by immature processes, but by poor development and quality management.

Parts availability

Unlike the main goal of assembly of having a stable production, the parts availability can be measured directly. As one of the main drivers for enabling a successful and stable ramp-up, parts availability needs to be ensured, and can easily be monitored by comparing the available parts versus the needed parts. Evaluation at the assembly line of missing parts then provides a comparison with the system output, thus refining the logistic data accuracy.

Establishing delivery concepts

Monitoring the delivery concepts can reveal issues in data accuracy and missing delivery concepts or unclear ones can lead to missing parts. As such, the gathered data includes a ratio between parts with delivery concept vs. total parts. Further detailed, this then provides whether the delivery concept was appropriate for that part or not, e.g. damage protection.

Validation of packaging concepts

The last chance to adapt to changes before series production, the ramp-up should be used to validate packaging concepts, as damages to customer products result in difficult rework, for instance if an entire lot is damaged. As a result, all packaging concepts with significance to the customer should be tested against potential danger to the parts. The final KPI is an OK-NOK comparison as with the workforce qualification.

Stability of series production

The control of the series production is performed according to the standard process, as it is expected that nothing should change, e.g. the throughput times and quality figures of an existing product.

Meeting series condition

The final step towards ending the ramp-up phase is meeting the series condition. Measuring the condition of the new product’s behaviour with the tools of the series process with the values of both process chains matching one another is the preferred method.

5.3 Identifying Potential Issues

Following up on the initial data gathering, the data must be transformed into information. As stated in the entrance of Chapter 5.2, steering can either apply KPI for the entire system or break it down to provide information for every workstation. By doing so, every workstation is compared against the targets of the specific phase, and deviations from the target become transparent. A comparison between two groups can further be used as a benchmark, giving additional possibilities for improvement.

The linking of gathered data to the product it was observed on also leads to the ability to comprehend the KPI's trend. This information is vital on understanding whether the parameter is stable at a certain level, or decreasing or increasing. After gathering the raw data, it is refined to a mean value, or in cases were beneficial, calculated to a trend curve[246]. The value defined by calculating the mean or the limit is then used as the representative value of a specific station.

The summation of every single workstation provides the user with a total overview of the system. IT-Programs quickly match the gathered data, and assigning workstations with their KPI, and thus generating an overview. Visualising the workstations in charts helps seeing correlations and eases up further work. Additionally, by using statistical software the identification of correlations is enhanced.

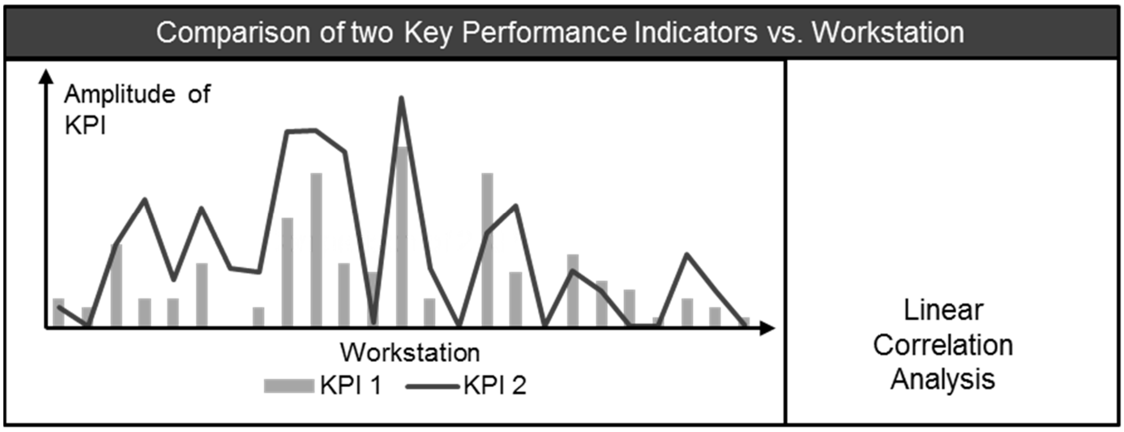


Figure 5-1 Correlation analysis of two KPI

Figure 5-1 shows such a potential analysis, with the Y-axis being the amplitudes of the KPI according to their respective station. The right part provides a statistical analysis, determining the values have a correlation value of approx. 0.7[247].

Checking the cross impact of targets is useful for finding the core issues of the problems, as the fulfilment of a target might be only achievable when fulfilling another one(e.g. a high amount of rework can be a result of parts not available or untrained workers).

As the outcome of this analysis, workstations have clear key performance indicators. Since time is usually scarce during ramp-up, a prioritization strategy needs to be applied, in order to catch up on the missed goals.

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[246] Cf. Chapter 2.5.4
[247] Cf. Chapter 2.3.4

5.4 Understanding Main Issues

Focusing on the main issues relieves the project team from being overloaded with work, and a prioritisation is needed. This can be achieved by a Pareto[248] analysis or similar, showing the issues, where if worked upon the best results in regards to the target are achieved.

The result of the previous step is afterwards set into perspective, and from all issues, the main ones are defined. Every target agreed upon before is weighted against its potential risk to influence the stability and success of the ramp-up. Depending on the company and phase of the product introduction, different objectives are deemed of being high risk. While in an early phase, recording too little problems is a danger to mature the product, the problems found should decrease as the product moves towards its start of production. On the other hand, achieving takt time stability is less of a target when the product is introduced new to the associates, but once launch onto series production line starts, the objective is to keep the production fluent.

The key point of the method and data gathering is to keep in mind, that although issues in one phase might be solved by start of the next, experience shows that missed targets are carried from one phase to the next, especially if the reaction time between two phases is very limited. This effect is highly dependent on the organisation’s capabilities. Benchmarking the current project with earlier launches gives the management the ability to anticipate the impact of missed targets onto the succeeding phase. Therefore, an analysis of the main issues should consist of:

- Target weighing of previous and future build phase
- Target comparison with past product introductions
- KPI matching to next phase

To improve the understanding for the execution of such an investigation, a simple example out of a company is given:

The introduction of a product is transitioning from a quality phase towards a volume phase. A correlation was found between the throughput time and the amount of rework. After thorough investigation it was concluded, that the throughput time was actually achieved only due to missing parts. These parts had their processes skipped, and as a result, the throughput time was achieved, but on the other hand, the rework time was increased, as the products were missing parts. Hence, the main issue was not the poor product maturity, but the parts availability to the line. Focus should therefore be given to establish robust logistics processes, and not onto reengineering parts. Further analysis revealed, that only a few missing parts where resulting in a majority of the rework. Due to a pre-assembly process not being accurate enough in its takt time, the delivery times

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[248] An analysis based on the thoughts of Vilfredo Pareto, describing the occurrence that e.g. 20% of the goods in a warehouse hold 80% of the worth. Also known as 80-20 rule or ABC-rule.

where not matched. With resolving the underlying process issues, the company is able to stabilise the rework times, freeing up capacity.

In addition to analysing with data, approaches such as the 5-why method, an Ishikawa[249] Graph or similar can be used to understand the main problems. The method emphasises on understanding the underlying issues, and connecting dots to a bigger picture. Only then are the prerequisites for a solution fulfilled, and stability ensured.

5.5 Mitigating with Quick Wins

By having defined issues in the previous step, problem oriented solution finding can start. Although series conditions demand for a stable and long-term solution, quick wins can lead to a mitigation of high-risk issues, and a stabilisation of critical targets to a stabilisation of the assembly process.

The focus of stabilisation lies on the two main objectives. First, for a stable and continuous production, assembly is obligated to achieve throughput times and takt times in order to keep production performing on a high level. Second to that, logistics must ensure parts availability to keep the takt time stable.

The first goal of achieving a stable production can be influenced by adjusting each of the secondary targets, depending on the core problem. Especially once the assembly is performed on a mixed model line, the throughput and takt time may not vary too much from the series' assembly. To achieve this goal, certain tasks can be prior to the start of building. If knowledge of the issues is on an adequate level, decoupling pre-assemblies or similar process of workstation that have an exceeding takt time, results in saving precious inline assembly time. As a second solution, training and qualifying the associates on those processes which take a lot of time, or that deviate from the planned takt time by a lot, can help decrease the process time, and thus reduce the takt time again. As with the pre-assembly decoupling, obvious rework can be performed before, until supply has caught up to the new standard part needed. Only the identification of problems cannot, and should not, be adjusted to save time. In contrast, the problem identification needs thorough execution, so that issues are not carried into the series process.

Parts availability issues are negatively influencing the takt times, and most problems result from unclear processes and bad data accuracy. Some issues are nevertheless a result of bad handling and bad packaging. During a pre-series build, parts are not available in high numbers, as parts are rarely produced in a full capacity series environment. Small damages occurring, can lead to parts being blocked for production, and in consequence, supply is decreasing throughout the build phase. Damaging parts

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[249] A problem analysis method named after Kaoru Ishikawa as part of the Toyota Production System

during assembly and reworking them afterwards is also leading to a higher consumption of parts than expected. As a mitigation step, having a small safety stock can ensure the production, and enable a stable part supply.

After having performed a first set of quick wins, the situation needs to be re-evaluated, and the focus might potentially shift towards other points of interest. Integrating these changes into the next phase, and following them, is crucial for success.

5.6 Implementing Changes

The topic of implementing changes into the system needs thorough discussion, and this thesis can only present the general idea of the topic in the context of ramp-up. Nevertheless, a general concept is given, and a starting point is provided.

The general acceptance to changes is increased during the ramp-up phase, as the production is anyway in a tumultuous state. Therefore, the adaptation of new processes and their adjustment in specific cases is a daily regular. This fact bears the danger, that changes decided on in previous phases are implemented without full communication and documentation.

The proposal is to have a distinct system developed for implementation of changes during production ramp-up, where the documentation of changes is done without too much of an administrative effort. Some deviations from the standard process might only occur once, some are performed for trying new approaches, but their effect still needs to be validated and documented.

Every change should therefore follow the general process of change management, meaning having defined a target condition, a target date and a responsible person[250]. As it is expected that everything that needs to be changed has a reason in one of the targets defined, the comparison of pre-change and later condition state with KPI can be used to verify the effectiveness of the implemented change.

The correct communication needs also setting up, so that all process partners are aware of changes and adaptations. System support can improve the condition, but solutions based on offline applications, such as MS EXCEL or similar, pose a threat to the communication system, as a multiuser platform might result in changes not being recorded or badly documented. In consequence, the communication system and the documentation system need to be linked and set-up for example as a web application. The essential part is that it should be used as a system to support the users, and push information to them. Relying only on putting it into the system without automatically notifying others of changes results in the opposite effect, as people start communicating only via the system and without the messages valuable time is lost.

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[250] Cf. Chapter 2.5.4

5.7 Real Time Management

All steps before have dealt with the idea of managing the risks of the new product launch before production starts. Once assembly has launched the validation of all changes and process steps starts. As an additional part of the method, real time management (RTM) provides production steering with quick feedback on the current state of production. By usage of different trend analysis, and including experience from earlier ramp-ups, the future state of the system can be estimated.

The trend curve can be determined by statistical programs again for those where the trend is unknown. Sometimes on the other hand, the expected trend curve follows a predefined function, such as assembly time decrease being described by the learning curve. With this information, a KPI overview on the estimated final state can be determined, and deviations from the target can be acted upon.

Another benefit of a RTM system is the ability to know when an assembly problem is becoming critical as early as possible. This especially applies to takt time and parts availability once launching the new product onto a mixed line with another existing product. In the case of takt time for instance, companies can pull in a buffer after the launch of the newly introduced product. This buffer is then slowly consumed, as the workstations exceed their takt times.

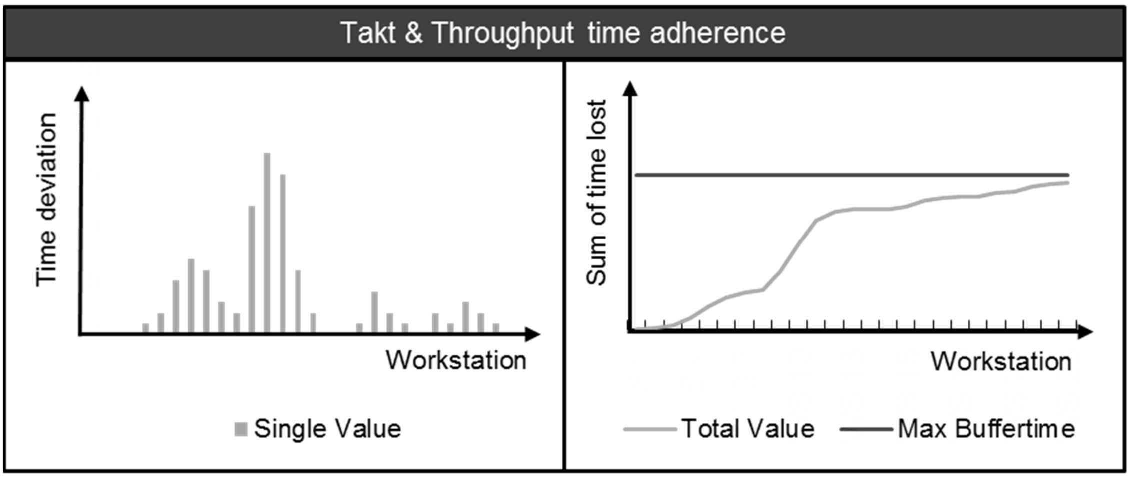

Figure 5-2 Expected buffer usage in case 1

Figure 5-2 has depicted two graphs. The one the left is showing the deviation from the takt time per workstation, while the right one shows the summation of all exceeding times. It shows that a high consumption of the buffer in early stations does not necessarily mean that the buffer gets used up fully until the end of the build phase. In this case, process changes like pre-assembly decoupling and usage of floaters should not be used, as the maturity and try-out of assembly processes suffers.

In contrast to that, Figure 5-3 shows a situation where the summation of all takt time exceedances leads to a negative buffer. In consequence, the assembly line has to stop, and production volume is lost. Though this lost volume may not be high, problems in production stability of the ramp-up can lead to instabilities in the entire production system.

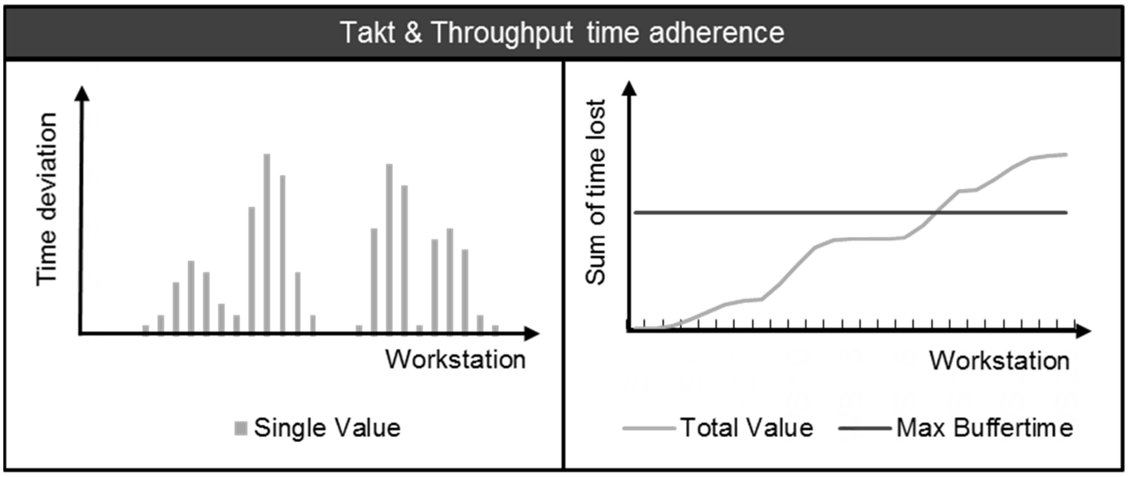

Figure 5-3 Expected buffer usage in case 2

To counter this, several possibilities exist. The concept of decoupling[251] was already introduced and needs no further elaboration. Another trivial concept is catching up to the buffer by working through breaks and other phases of rest. This can only be used as a temporary solution, as once the series worker take over from the project team, the ability to skip or shift breaks to later times is demanding too much.

A similar concept to decoupling is the usage of so-called floaters. By using free capacity from workers of other stations, or additional workers, work steps can be taken over by them, decreasing the total takt time. These tasks are only part of the entire work content, and once finished, the employee returns to his primary station, or if he is a full time floater, to the next station where additional work capacity is needed.

In case of missing parts or late parts, the flexibility of the worker and work content is essential to mitigate the results. By reordering the sequence of steps, some parts are used later, and logistics has an additional window of opportunity to deliver parts. It has been observed that installing a “help desk” for logistics issues decreases the communication time, and the response time to parts availability issues had a massive improvement.[252]

Managing the workstations is another set of tasks. The implementation of a decision tree is to be thought of, to ensure fast response to occurring disturbances, without causing even more instabilities. Generally, all assembly systems should deal with the problem what to do when the assembly process takes too long, or critical parts are missing. The decision tree needs to be in place before launching the first car onto the production line,

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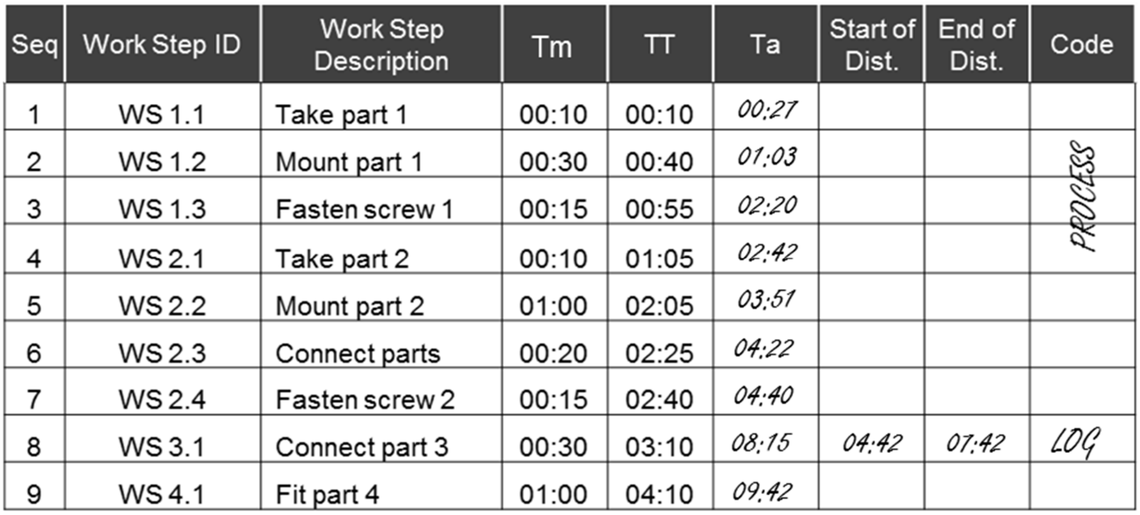
[251] Cf. Chapter 5.5

[252] Based on expert knowledge and observations in an industrial environment

and management is required to agree on possible strategies. Then, if known when disturbances start occurring, the following tasks are already set-up, and everything is performed in a controlled way.

In order to know when these problems occur, a monitoring strategy has been set up to quickly record observed issues systematically. The proposed monitoring system's basics are shown in Table 5-3. It consists of nine columns, each holding information relevant to the process.

The first five columns are providing the observer with information needed to evaluate efficiently during the build and to understand where process deviations are occurring. Column "Seq" shows the sequence order of the work step used for the checking if the steps are performed in the order pre-defined. "Work Step ID" is used to identify the process step with a digital system, and "Work Step Description" is needed for identifying the current process step when observing the worker at the line. The times in column "Tm" are the times defined for the process step by a previous time study, and the adjacent "TT" column is the summation of these times.



Seq	Work Step ID	Work Step Description	Tm	TT	Ta	Start of Dist.	End of Dist.	Code
1	WS 1.1	Take part 1	00:10	00:10	00:27			
2	WS 1.2	Mount part 1	00:30	00:40	01:03			PROCESS
3	WS 1.3	Fasten screw 1	00:15	00:55	02:20			
4	WS 2.1	Take part 2	00:10	01:05	02:42			
5	WS 2.2	Mount part 2	01:00	02:05	03:51			
6	WS 2.3	Connect parts	00:20	02:25	04:22			
7	WS 2.4	Fasten screw 2	00:15	02:40	04:40			
8	WS 3.1	Connect part 3	00:30	03:10	08:15	04:42	07:42	LOG
9	WS 4.1	Fit part 4	01:00	04:10	09:42			

Table 5-3 Workstation sequence analysis sheet

The other four columns are used for input information. "Ta" is the actual time when the process step was finished. This mode of measurement is installed primarily for user friendliness, as the clock does not need to be managed, and a simple noting is quick when work steps are sequenced after each other. When a disturbance occurs, the time at which the disturbance has started is noted in column "Start of Disturbance", and the same is for the end. With this system, the total time of a disturbance can be easily calculated after the measurement, and the summation of the differences gives an overview on the total time lost. The last column "code" gives the user the opportunity to state what the disturbance was. Table 5-4 provides a proposal for those codes and their associated KPI times.

	Code	KPI	Description of KPI
LOGISTICS	LOG MISS	TLmiss	Time lost by searching for part (stops when process steps is skipped) + time added after takt is finished
	LOG WRONG	TLwrong	Time lost by fitting wrong part, searching for part (stops when process step is skipped= + time added after takt is finished
	LOG	TL	Unclassified time lost due to logistics
TOOL	TOOL MISS	TTmiss	Time lost due to missing tool
	TOOL JIG	TTjig	Time lost due to missing jig or fixture
	TOOL HANDLE	TThandle	Time lost due to difficult handling or poor quality of tools, jigs and fixtures
	TOOL	TT	Unclassified time lost due to tooling
ENGINEERING	ENG FIT	TEfit	Time lost due to difficult fitment of parts, e.g. small tolerances
	ENG ALIGN	TEalign	Time lost due to difficult alignment of parts, e.g. holes for screws
	ENG RELEASE	TErelease	Time lost due to faulty release and need of rework to continue
	ENG INSTRUCT	TEinstruct	Time lost due to bad work instruction, e.g. torque too high and thus spinning screw
	ENG	TE	Unclassified time lost due to engineering issues
MISCELLANEOUS	PROBLEM	Tproblem	Time lost de to problem investigation
	WAIT	Twait	General time lost due to waiting (for associates, engineers etc.)
	PROCESS	Tprocess	Time difference to time planned if no disturbances applicable

Table 5-4 Proposal for time related KPI and measurement codes

The four different groups of disturbances relate to process partners responsible for solving the issues. Grouping them in this way, the responsibilities for solving issues are clear and problems investigation starts faster. Although the miscellaneous issues cannot be generically addressed to a certain process partner, waiting time and longer process are an indicator for unbalanced work content or untrained associates.

Coming back to the case of the observed station in Table 5-3, work step 3.1 had a missing part, leading to a disturbance of 3 minutes. Work steps 1.1 to 2.2 where taking longer than expected, without any disturbance observed, resulting in the possible conclusion that the process is not mature enough, or showing a lack of qualification. If the time deviation is occurring on every product without variance, either the process needs to be re-designed, or the time study needs verifying.

By analysing every single workstation throughout the build phase, every issue is recorded in detail and patterns observed. Controlling the production in real time, and feedback of changes directly into the project result in the success of the current, and future build phases.

5.8 Increasing Process Knowledge

The final step of the methodology is a synthesis of all the previous data and information gathered. By matching the targets defined in Chapter 5.1 with the data obtained from the real time management described in Chapter 5.7, knowledge on the actual problems is refined and the accuracy of further planning can be increased. The accumulated data is then fed back to the database, correlated with the initially gathered information. The background of this step is the integration of Lessons Learnt in a systematic way. For a good analysis and improvement, a classification of the process disturbances might be introduced, depending for instance on departmental responsibilities or the process organisations.

The KPI defined in step 2 are enhanced by usage of the data gathered from step 7. For accurate knowledge and reflection on issues, the time recordings are used by condensing them to different KPI, each of the times grouped to one of the three general losses of Nakajima. Figure 5-4 displays the calculation scheme. The volumes used in the approach of NAKAJIMA or GARTZEN are substituted with the calculated lost times due to performance issues and quality, and thus the new method is relying on time only. Therefore, the entire OEE is not calculated by defining the three different subgroups before, but rather as the ratio of Value added Uptime to Total Time:

$$OEE = \frac{Value\ added\ Uptime}{Total\ Time} \qquad \text{Equation 5-1}$$

This KPI can then be calculated for every single workstation, each individual worker, or if zoomed out, for the entire production phase. Production control can then undergo an investigation on which stations are most critical based on the OEE, and improve the efficiency by prioritisation. The knowledge of the ratios of process issues to each other and to the overall time enables management to target specific problems, and thus improve the output of future build phases.

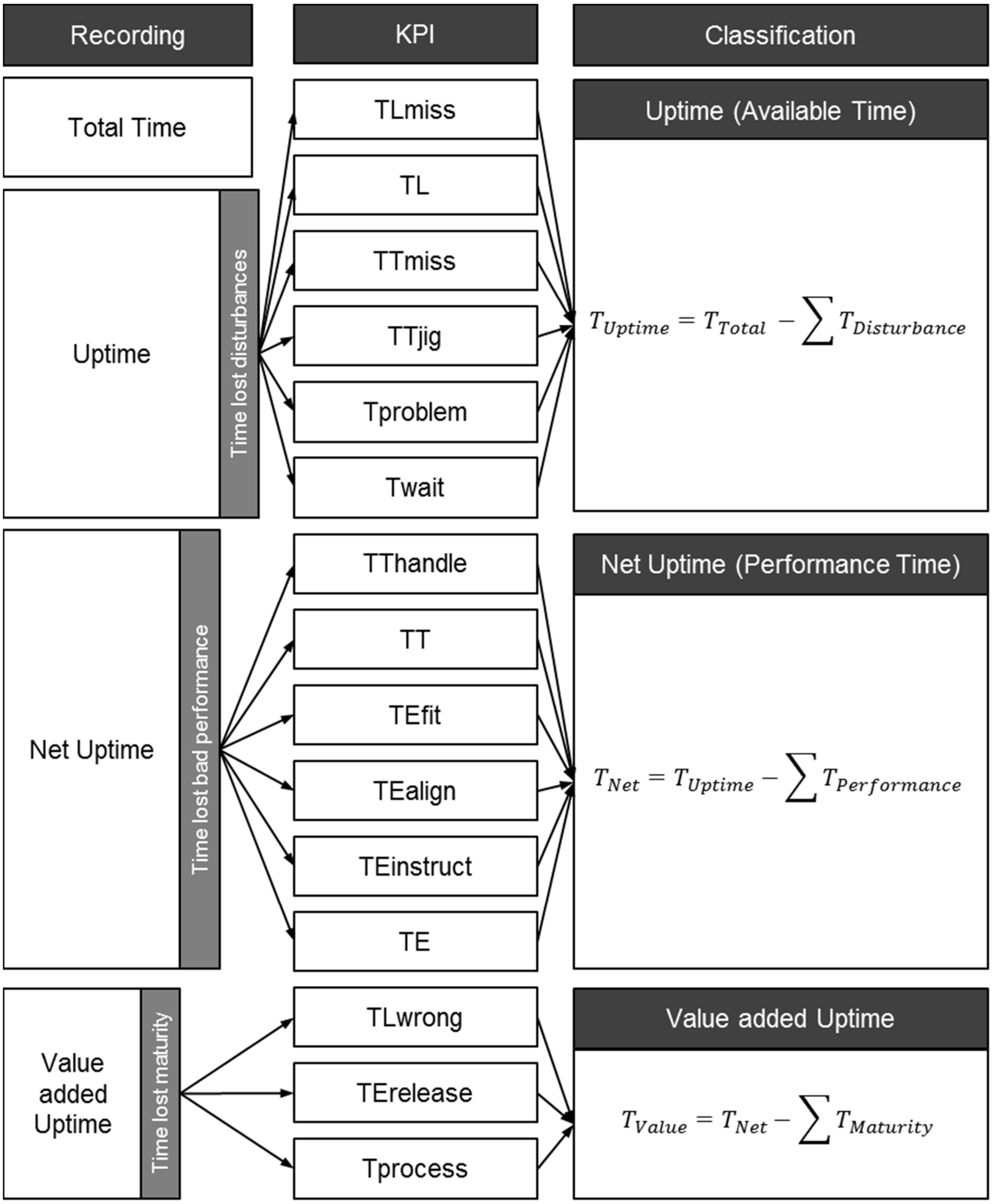


Figure 5-4 Calculation table for value added uptime

The specified targets and gathered data from the first two steps set the base for the methodology. With analysing and prioritisation, mitigation of risks is easier, and management can focus their steering activities accordingly. Implementing changes and monitoring the progress of the product on the assembly line, gives the steering circle the ability to react quickly to new disturbances, and decide precisely on actions. Knowledge enriched with data gathered from real time monitoring helps the business throughout the entire ramp-up. The methodology presented is therefore not only useful for determining and achieving a state of stable production during one specific ramp-up phase, but also for improving the outcome of those to follow. In the end, the production of the ramp-up is uplifted to such a level that reaching series conditions is no difficulty, and the targets of quality, cost and time are met within their limits.

6 Application at Rolls Royce Motor Cars

This thesis, especially chapters 4 and 5, were developed during a master thesis placement at Rolls Royce Motor Cars in Chichester, United Kingdom. Staff of the Institute of Innovation and Industrial Management at Graz University of Technology in cooperation with Rolls Royce Motor Cars (RRMC) academically supervised the thesis.

The resulting methodology was elaborated and applied during pre-series build phases for a newly developed model at said location in 2016 and beginning of 2017. Chapter 6.1 deals with the history of said company from its beginnings onwards, and an overview of the organisational scope of the placement.

The following Chapter 6.2 sets the stage of the scenario observed. The analysis performed during and after the first pre-series build phase, followed by first measures performed in-between a short period between two phases is the topic of chapters 6.3.1 and 6.3.2. The last two sub-chapters 6.3.3 and 6.3.4 deliver and in-depth analysis of the second observed build phase, which was split into two batches, concluding in Chapter 6.4 were the application of the methodology is discussed.

6.1 Rolls Royce Motor Cars Ltd.

Rolls Royce Motor Cars is a world-renowned enterprise, providing British luxury automobiles for more than a century. Sub-chapter 6.1.1 gives an overview of the rich history of the company. In 6.1.2 the author’s position in the company is discussed, as well as the organisational relevance in the enterprise. Chapter 6.1.3 finalizes the status quo of the company by introducing current topic related processes at RRMC and their mother company, the BMW Group.

6.1.1 Historical Background of Rolls Royce Motor Cars

The founding of Rolls-Royce is one of the milestones of British car manufacturing. With the encounter of Henry Royce, a self-taught engineer from a poor upbringing, and Charles Rolls, a motorsport enthusiast and car dealer with a degree in mechanical engineering, a new chapter in automotive marksmanship was opened. By 1903, Henry Royce had built his very own first petrol engine, the *Royce 10hp.* A meeting was arranged between Royce and Rolls, as the latter was frustrated by imports and looking for British products. Upon their meeting, mutual agreement was found in producing motor cars with this new engine, and selling them branded as *Rolls-Royce.* With Claude Johnson, a former partner of Rolls, a competent managing director was found who understood the early concepts of marketing. With demonstrating the cars to the open public, and offensively advertising the car as the “best car in the world”, Rolls-Royce became a synonym for excellent engineering.[253]

With production of the “Silver Ghost” starting in 1907, by 1913 Rolls-Royce had finally earned the self-given title of “best car in the world” by successfully completing the 14.731 mile long Alpine Trial. Production of the early Ghost was halted in 1925, only to be succeeded by the “Phantom I”, the pro-genitor of the very representative limousine that defines the marque Rolls-Royce until today. World War I came over Europe, and as a participant, Britain demanded Rolls-Royce to produce aviation engines as well. Again, the competence of the company was established, as the produced engines where top-notch, and propelled the later Spitfires and Hurricanes during World War II. During the economic crisis, the enterprise successfully bought competitor “Bentley”, and production of both brands was transferred to Crewe.[254] [255]

After financial disturbances whilst developing a new aero engine, the RB211, the state had to step in and the company was brought under state ownership. By 1973, the motorcar section was separated, and Rolls-Royce Motor Cars Limited was founded as the successor of the motor cars branch. With new models and under the ownership of the British defence company “Vickers”, production continued until 1998. Rolls Royce Motor Cars was again sold, and with the BMW Group, a company wanting to increase their portfolio, a buyer was found.[256] Contractual differences between BMW and Volkswagen, resolved in BMW acquiring the sole rights to produce motor cars with the brand Rolls-Royce. With now a new brand in the portfolio, but no production facility, as the factory was acquired by Volkswagen along with the Bentley brand, BMW built a new factory located near Goodwood Estate, West Sussex. In 2003, the first new Phantom under BMW tutelage rolled off the production line.[257]

The production of the Phantom, was soon afterwards adopted, with new models launched. The Extended Wheelbase model and Coupe derivatives where introduced. In 2009, a new model was introduced, smaller in comparison for everyday use. Under the name of “Ghost” this smaller model was launched on a separate production line, as the concepts and volumes where deviating too much. Added with a coupe and convertible version in 2013 and 2016, the once calculated capacity of 800 units for the factory was far exceeded. Figure 6-1 shows the past development of the product portfolio. By the end of 2016, a yearly production volume of approximately 4000 units was achieved, and a continuing trend shows a promising future.[258]

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[253] Rolls Royce Motor Cars Ltd. (Rolls & Royce)
[254] Rolls Royce plc.
[255] Rolls Royce Motor Cars Ltd. (History)
[256] Rolls Royce Motor Cars Ltd. (History)
[257] Rolls Royce Motor Cars Ltd. (Goodwood)
[258] Expert interview during placement

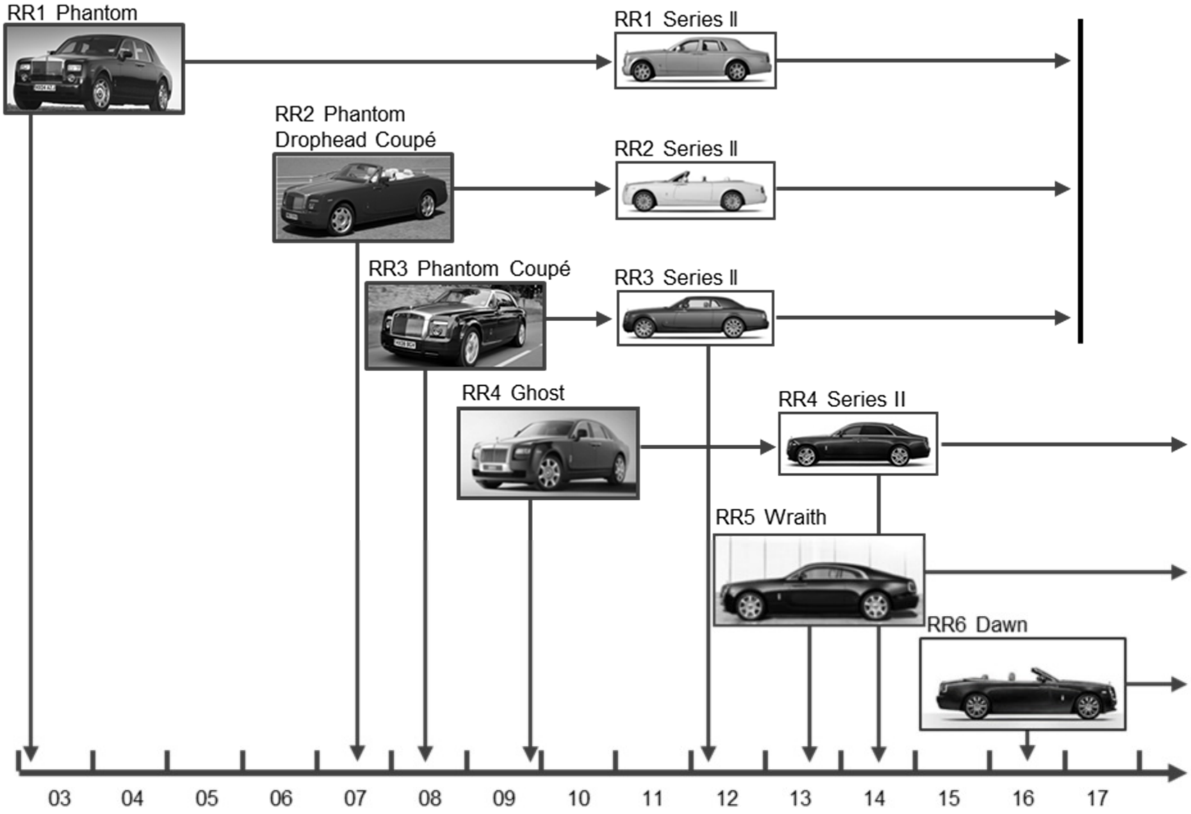


Figure 6-1 Product portfolio of Rolls Royce Motor Cars

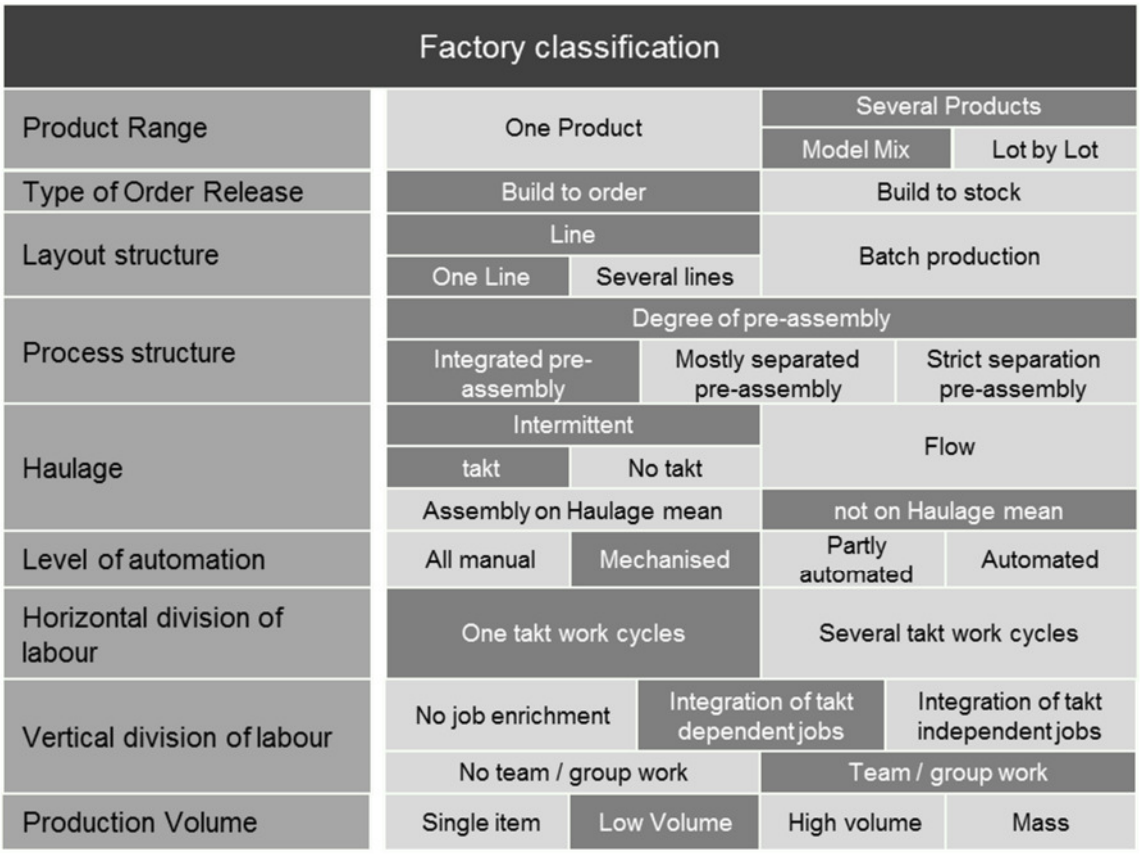
With 2016 marking the start of a new production system, all products produced on one line, the challenges of introducing new models to the system are increasing significantly.

6.1.2 Assembly and Logistics at Rolls Royce Motor Cars

Prior to the practical evaluation of the methodology, an introduction on the assembly and logistics system at RRMC is provided.

The entire production system had several changes during the 6 month period, as a beforehand planned transition from multi-line production to single mixed model line production was performed. The validation of the new assembly system was in fact performed with the ramp-up of the new model. In addition to that, the introduction of a new third party logistics service provider added new complexity to the organisation.

The factory is unique in the organisational context of the BMW Group. By having the lowest production volume of all plants, and having the highest degree of customisation, many processes are specifically customised onto the facility at Goodwood. In the past, the plant featured two separate production lines. With the run-out of the phantom model, its production line was omitted, and all future products are assembled in the one line system (OLS). The remnants of the previous Phantom line, called South Line (MLS) are being used for testing, improvement of assembly processes, and pre-series production. With the orientation onto high customisation, called “Bespoke content”, the facility never reached a high degree of automation. This is partly due to the low volume, as well as to the uniqueness of the products. With the introduction of the OLS, the assembly takt times were also highly changed. From previously producing 16 units per day (upd) on the main line with a takt of 56 minutes and 2 units per day on the MLS with 182 minutes, production was increased to 20 upd, with a takt time of 44 minutes and a two-shift system. Figure 6-2 summarises the factory classification according to the definitions provided in Chapter 2.6.1.



Factory classification				
Product Range	One Product		Several Products	
			Model Mix	Lot by Lot
Type of Order Release	Build to order		Build to stock	
Layout structure	Line		Batch production	
	One Line	Several lines		
Process structure	Degree of pre-assembly			
	Integrated pre-assembly	Mostly separated pre-assembly	Strict separation pre-assembly	
Haulage	Intermittent		Flow	
	takt	No takt		
	Assembly on Haulage mean		not on Haulage mean	
Level of automation	All manual	Mechanised	Partly automated	Automated
Horizontal division of labour	One takt work cycles		Several takt work cycles	
Vertical division of labour	No job enrichment	Integration of takt dependent jobs	Integration of takt independent jobs	
	No team / group work		Team / group work	
Production Volume	Single item	Low Volume	High volume	Mass

Figure 6-2 Factory classification Rolls-Royce Motor Cars[259]

Initially planned for less than 1000 cars produced in a year, the factory is under high stress for space and area, as the production volume increased to 4011 units in 2016. The former areas designated to logistics were removed from the site, and in 2015 located to Bognor Regis, 10km away from the factory. Parts are delivered to the site with different material flow concepts, depending on the demands from parts quality and part size. Most of the value stream is transferred through kits, so called “carsets”, which are then provisioned to the assembly line when needed. Part delivery is split between the logistics service provider (LSP) and internal physical logistics, once the parts are at the factory. This means, in case of missing parts they cannot be quickly reordered, as the external storage leads delivery times of 30 minutes.

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[259] Factory classification by Expert interview, referring to Chapter 2.6.1

General production is following the route as shown in Figure 6-3. The finished bodies in white are delivered from Dingolfing, Germany to the paint shop (not shown in picture). After painting the bodies, the cars are launched in sequence onto the assembly line. The current line has 25 workstations, of which two represent a quality gate. The numbering of workstation follows a generalised BMW system, with station 050-010 always being the marriage station. The system has one U-turn, used for adapting to different volumes. Small Kanban parts are stored on site, and follow their own value stream. On the right side of the picture the MLS is shown, where no regular assembly takes place.

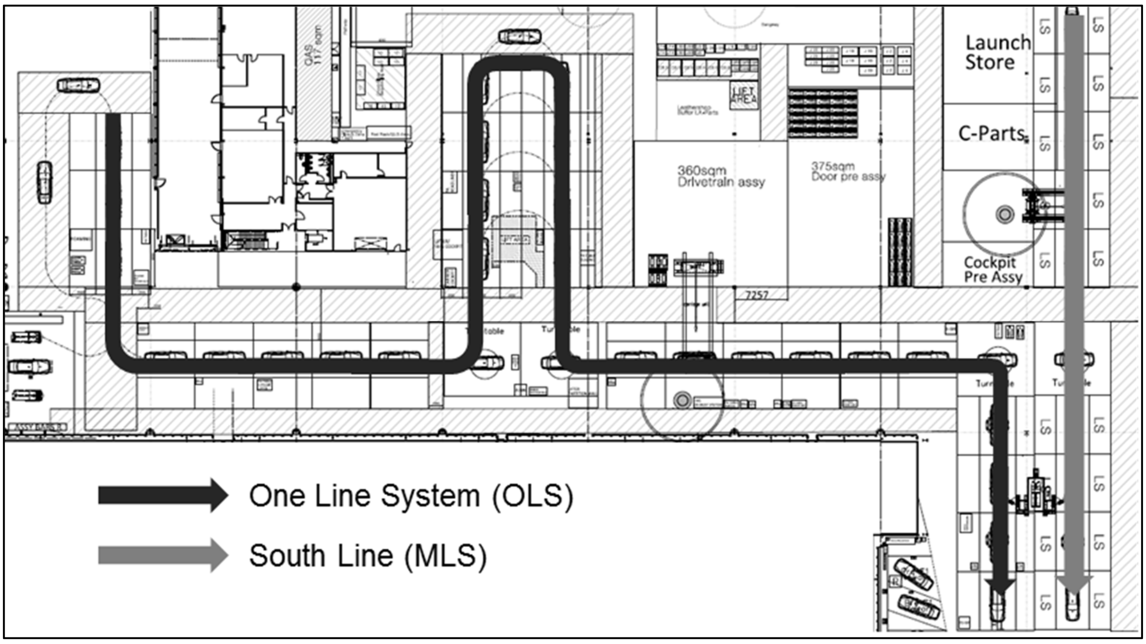

Figure 6-3 Assembly layout at RRMC

6.1.3 Generic Ramp-Up at Rolls Royce Motor Cars

As part of the BMW Group, the ramp-up process follows the general BMW process. Engineers headquartered in Munich, Germany, develop every product. Dependent on being only a derivative or a new model, the development period can range up to 3 years. After that, production ramp-up starts with the first prototypes built in “Plant 0” in Munich. This first phase, called Bestaetigungsbaugruppe (BBG, Product confirmation) is for assembly to get a first introduction to the product. Parts and process are not at series condition, and the goal is to improve the initial state of product maturity. Logistics is still organised by headquarters, and suppliers are using prototype tools to manufacture.

After maturing the product for another year, the product is the first time introduced into the plant. Depending on the decisions of management, the product is either launched on the OLS or MLS. This phase is used to confirm process changes, and investigate still unresolved process issues. The volume is increased and production times and product quality are the first time monitored. By having progressed through the so-called Vorserie 0, (VS0, pre-series 0), the product enters the next phases, Vorserie 1 and 2 (VS1, VS2, pre-series 1 and 2 respectively). Parts are now produced under series conditions at the suppliers, tools and machines at the factory should be close to series maturity, and logistics is applying series packaging. VS1 and VS2 are used to further refine the product, and confirm the ramp-up readiness for the start of production (SOP). The last phase is the so-called Anlaufproduktion (AP, ramp-up production) approximately 2 months before SOP. Production is already at series condition, and cars produced are already customer products. Figure 6-4 shows these phases in the timeline of the general ramp-up process described by SCHUH.

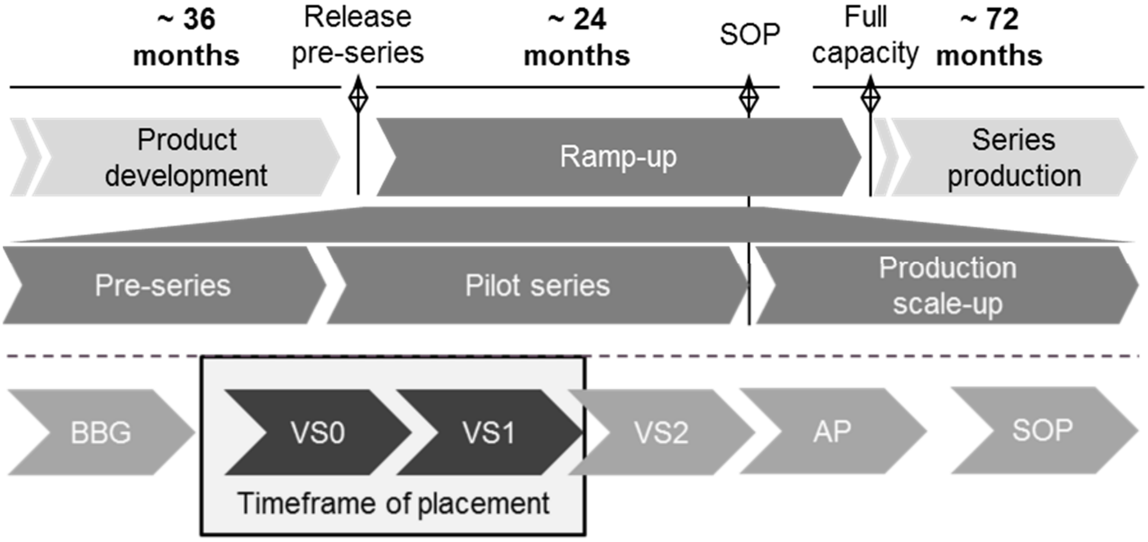

Figure 6-4 Production ramp-up at RRMC compared to phases in literature[260]

The readiness to produce under series condition is currently measured by the quality related KPIs "QZs[261]" and "QZf[262]". QZs is describing the quality level of the parts themselves, while QZf is measuring the degree of functional fulfilment. The readiness for production is achieved, if the problems captured in the internal product quality management system (PQM) are below a certain threshold. There is no other control over the assembly and logistics system, and KPI monitoring is not applied consistently.

6.2 Ramp-Up at Rolls-Royce

The timeframe of this thesis was set from start of pre-series 0 to the end of pre-series 1. The product at hand was entirely developed from scratch, and is forming the base for the next models to come, code named Rolls Royce New Model (RRNM).

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[260] Referring to: Schuh et al. 2008, p. 2

[261] Kundenorientierte Qualitaetszahl Standard / statisch, customer oriented quality figure standard

[262] Kundenorientierte Qualitaetszahl fuer Funktionalitaet, customer oriented quality figure functional

After having a turbulent, immature BBG, management decided to launch the products of VS0 on a separate line from series. Nonetheless, assembly worked under a near-series environment where reasonable, and main product features where already tested under series conditions on the MLS. All problems relating to product and process maturity, as well as product and process design where recorded. As the associates where building the cars, they themselves where raising incidents. In addition to that, takt times were written down, again measured by the workers themselves. Every worker was therefore monitoring himself. Direct process disturbances, i.e. missing parts or tools, were rarely recorded.

The main target was to improve product and process maturity, takt time was a secondary goal in the beginning. Recording actually started with car 5, and was not consistently carried out. With VS0 still having mainly quality related goals, takt time was primarily seen to confirm the maturity to launch VS1 together with series products.

After the production of all 38 cars, investigation was undertaken on whether or not the car can be produced in the given time on the OLS. Having recorded all takt times with their variances, the learning curve approach was undertaken to smoothen the times and give a final estimation on what the actual time would be, as shown by the graph in Figure 6-5.

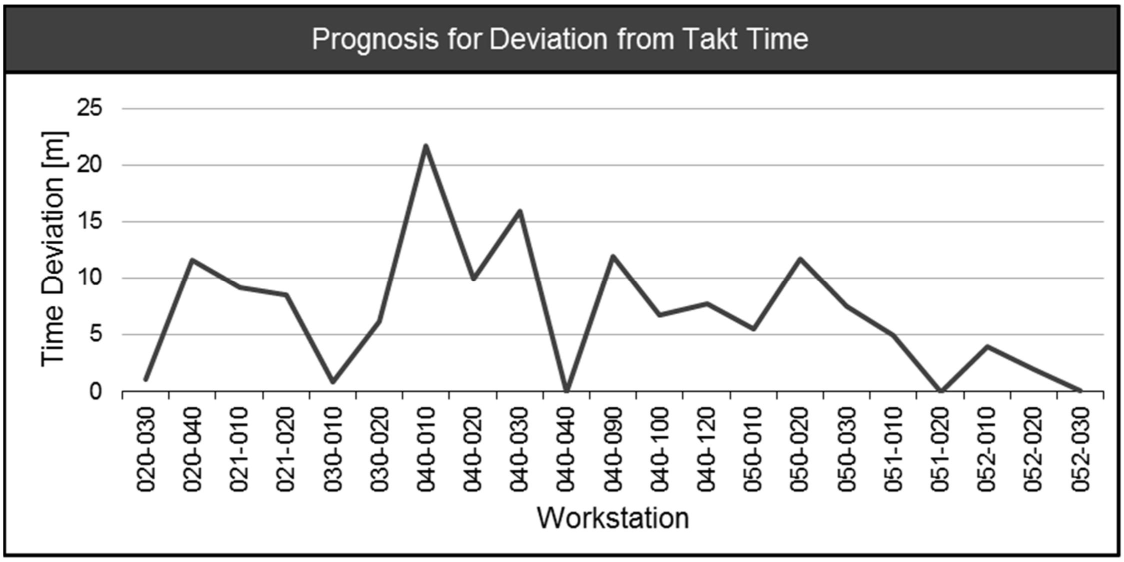

Figure 6-5 Estimated deviation from 44 minute takt by workstation

Although parts-availability being an issue during the entire build phase, the deviations where too high and too stable for that being the only reason. Same as the takt times themselves, the throughput times were also showing instabilities, especially towards the end. The graph in Figure 6-6 depicts the changes in throughput time, by means of the theoretical throughput time. As clearly seen, the entire throughput times follow the learning curve time, and nearly achieve the target of 18.3 hours, but this is only due to some takts being faster, and averaging out the entire throughput times. The last few cars had even bigger issues, and assembly was out of boundaries. The total delay was estimated to be 4.9 takts, meaning that the scheduled buffer time of four takts would be too little.

The resulting question were: Can the product be launched together in line with series production and how can stability be ensured once the product is launched.

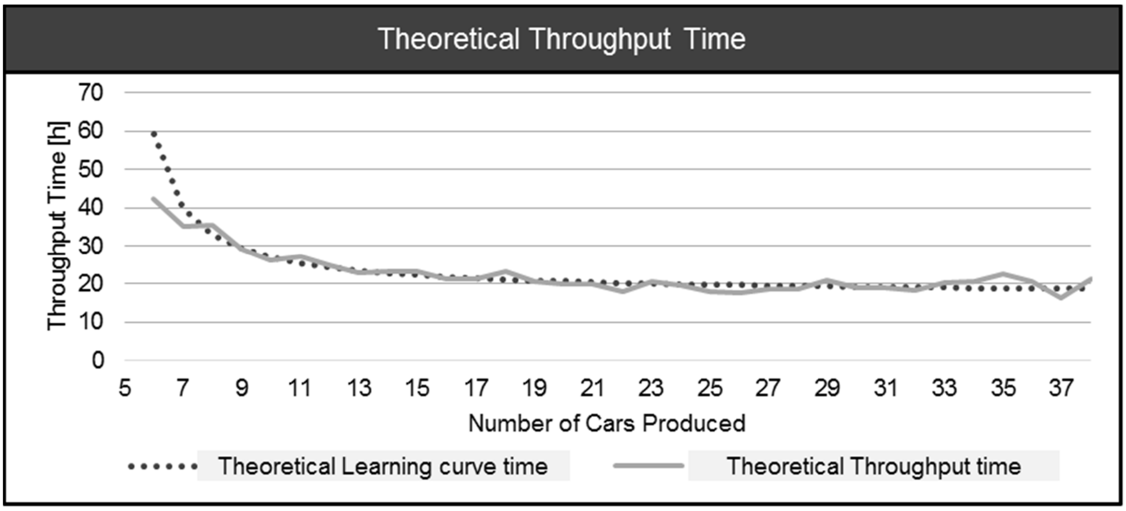

Figure 6-6 Measured throughput time vs. car produced[263]

6.3 Application of Methodology

The methodology described in Chapter 5 was the first time applied within a ramp-up at the Rolls Royce Factory at Goodwood, for transitioning the production ramp-up from a separate line to the OLS. The first part of the methodology, the set-up is discussed in Chapter 6.3.1, with the analysis of issues recorded during VS0. Building on that, the measures derived are discussed in Chapter 6.3.2, followed up by the active steering and control of the production during VS1 in Chapter 6.3.3.

6.3.1 Set-Up and of Analysis Pre-Series 0

Defining Targets

Application of the methodology started with the initial analysis of the targets of both, VS0 and VS1. As stated in the introductory chapter, the phase before VS0, the BBG was facing several problems. The threat of failure due to an immature product was present. To confront this situation, the targets defined by management deviated from the standard process, as a lot more effort was put into problem identification and product maturity.

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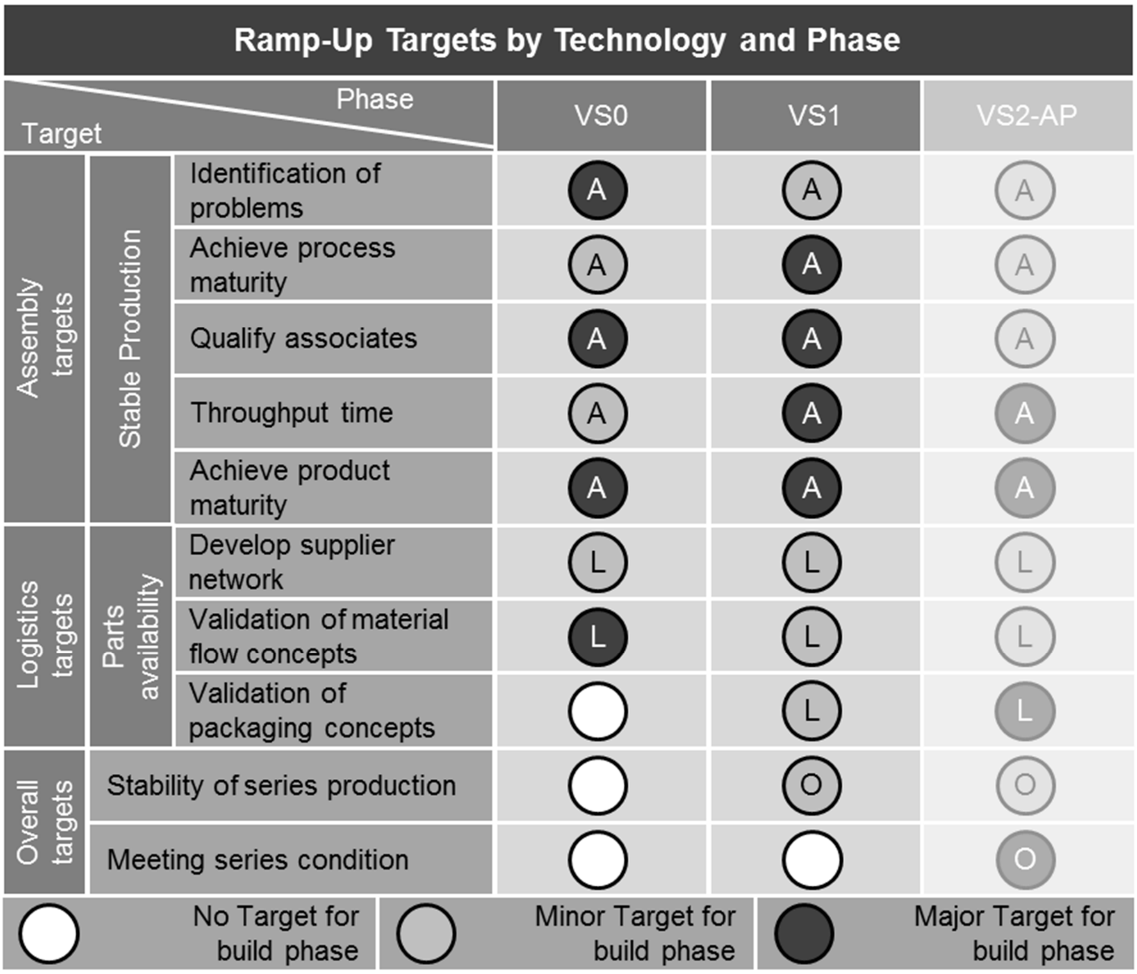
[263] Theoretical throughput time as defined as a target in Chapter 5.2. Calculation based on the total takt time recorded during the production of pre-series 0, decreased by recorded disturbances

The associates that were building products in the early phase of VS0 were mostly part of the project team, and their experience and qualification from the BBG was used as a measure to qualify personnel from the assembly line of the run out “Phantom” model.

Due to this focus on problem identification, only after having built the first five cars did the recording of takt time start, and throughout the entire build, the discipline to record them and adhere to them was not present. The production system automatically recorded throughput times, with daily production volume set to two units per day.

Processes were also not followed strictly, as parts availability was an issue in the entire build phase. Towards the end of the VS0 period, the issues were even increasing, as damaged parts were not reordered.

The supplier network was already fully functional, and logistics was primarily focusing on validating the set-up of delivery concepts. Due to the low numbers of parts, series packaging was unused until later phases. With the production starting on a separate line, the series process was not affected, and with an SOP in a bit less than a year, series condition was far from achievable.



Ramp-Up Targets by Technology and Phase

Target		Phase	VS0	VS1	VS2-AP
Assembly targets	Stable Production	Identification of problems	● A	◐ A	◐ A
		Achieve process maturity	◐ A	● A	◐ A
		Qualify associates	● A	● A	◐ A
		Throughput time	◐ A	● A	● A
		Achieve product maturity	● A	● A	● A
Logistics targets	Parts availability	Develop supplier network	◐ L	◐ L	◐ L
		Validation of material flow concepts	● L	◐ L	◐ L
		Validation of packaging concepts	○	◐ L	● L
Overall targets		Stability of series production	○	◐ O	◐ O
		Meeting series condition	○	○	● O

○ No Target for build phase ◐ Minor Target for build phase ● Major Target for build phase

Figure 6-7 Targets of RRMC from VS0 to VS2

Transitioning from pre-series 0 to pre-series 1, the targets shifted slightly. Figure 6-7 shows the different focuses during the two build phases, with an outlook onto VS2.

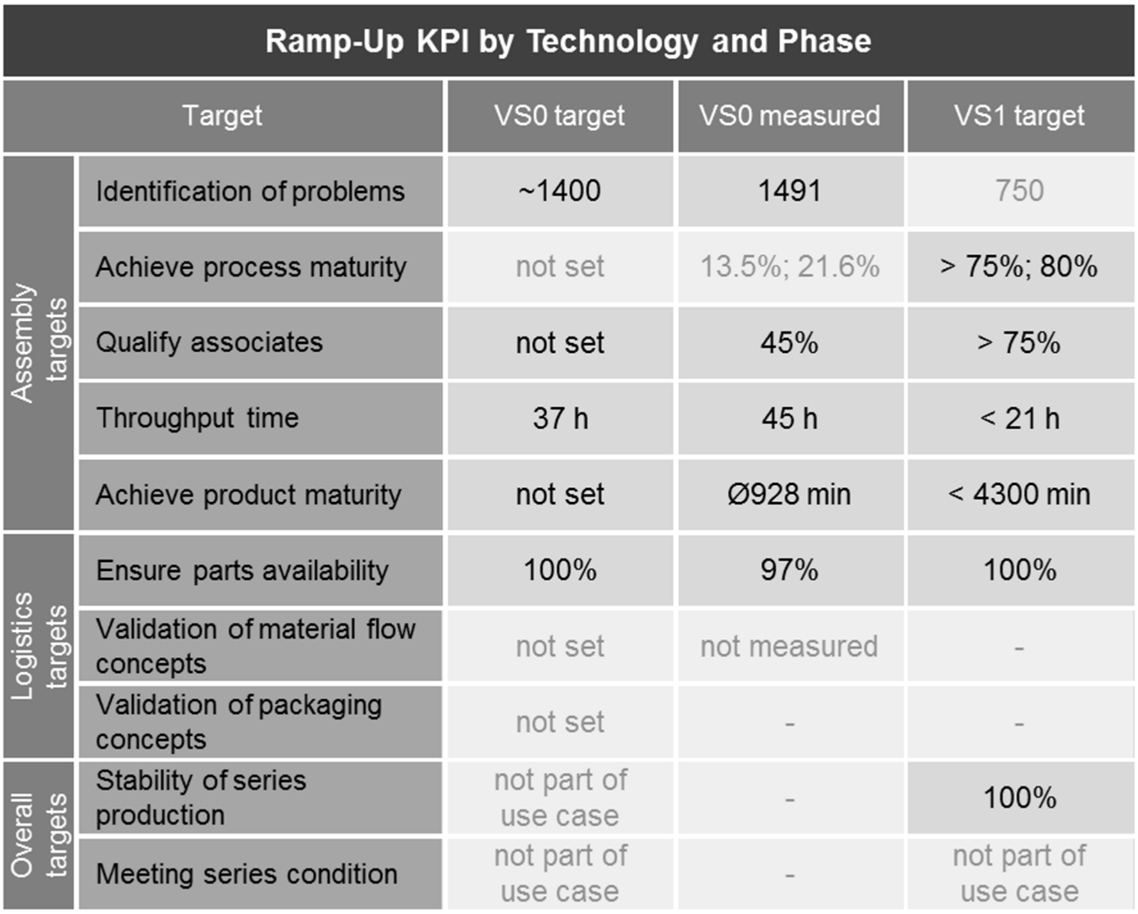
By coming closer to the start of production, the focus set onto achieving process maturity. Everything had to be done as planned and described in the build process instructions. The now qualified associates of the south line were integrated into the one line system, and training the workers of the OLS.

As the production was now on a mixed model line with the Ghost series, throughput time was a main target in order not to lose volume. The target of achieving a takt time of 44 minutes and thus a throughput time of theoretically 18.3 hours was paramount. The buffer time was set to four takts.

Problem identification was a minor target, as the over 1400 incidents observed during VS0 were still not solved completely.

Establishing database

The data already gathered from VS0, the takt times and throughput times in Figure 6-5 and Figure 6-6, where used as a base to investigate upon target fulfilment, as seen in Figure 6-8.



Ramp-Up KPI by Technology and Phase

Target		VS0 target	VS0 measured	VS1 target
Assembly targets	Identification of problems	~1400	1491	750
	Achieve process maturity	not set	13.5%; 21.6%	> 75%; 80%
	Qualify associates	not set	45%	> 75%
	Throughput time	37 h	45 h	< 21 h
	Achieve product maturity	not set	Ø928 min	< 4300 min
Logistics targets	Ensure parts availability	100%	97%	100%
	Validation of material flow concepts	not set	not measured	-
	Validation of packaging concepts	not set	-	-
Overall targets	Stability of series production	not part of use case	-	100%
	Meeting series condition	not part of use case	-	not part of use case

Figure 6-8 Target fulfilment VS0 and outlook VS1 targets

Out of the 37 associates working on the product, 45% where able to meet their process times at least once. Nevertheless, the processes where not stable enough, nor capable. Only 13.5% (C_{pk} above 1.33) of the processes where actually capable of performing to target and nearly 80% of the WS were variating too much (C_p above 1).

Parts availability was an issue, as every car had missing parts, but no record was found. Logistics provided an approximate number of 3% parts missing in stock after production has started, not counting missed delivery, wrong delivery to line or parts missing due to damage. An average of seven minutes was lost by every “missed” part, calculated by the average rework time for those cases that were reported.

In the next step, general project data was evaluated. Those sources of data include introduction of new parts, new and changed work instructions, as well as quality related numbers. The missing link of quality figures to workstation hindered a good evaluation, and thus the measurement of the rework time was the only reliable source of information to product maturity. Parts quality on the other hand was not observed at all, as the integrated process of the BMW Group foresees a quality check at the supplier.

6.3.2 Deriving Measures for Pre-Series 1

Preparations for the introduction of the new product were started immediately once VS0 was finished.

Identifying Potential Issues

As a first starting point, the takt times were considered in order to investigate the stations with the highest issues and highest impact. Due to bad data gathering many process issues were not found, and tackling the underlying reasons was not possible. Therefore, a correlation analysis was performed between various measured data. The result of correlating problem occurrence, process deviation, process change and takt time by workstation, offered interesting results for VS0:

- The occurrence of problems had a high linear correlation with the estimated takt time deviation from learning curve calculation (Figure 6-9)
- By filtering out one-off issues and quality issues (scratches etc.) the correlation was even further increased (R=0.777)
- The introduction of process changes had a relatively low impact on process times (R=0.367)
- Documented process deviations also played only a minor role (R=0.342)
- New parts had a high correlation with changing process times (R=0.672)

The fact, that the correlation of an observed problem had a high relation with the final time to be expected was a point of surprise. Problems and issues have been observed to 90% with the first five cars, which were not timed at all. This information and the fact the problem occurrence in VS0 and in BBG had the same pattern, led to the conclusion that the takt time was out of bounds due to the underlying maturity of the product. The identification of problems could have therefore been used as an early indicator for production issues.

From the analysis in Figure 6-9, two stations stand out: Station 020-030 and station 030-010. The first had no issues in its process itself, but as it was the first station the painted body was observed, many issues unrelated to the assembly were recorded, such as damage to the body, bad paint etc. Station 030-010 on the other hand was a station where several issues with the main wiring harness were collected, e.g. missing connector, wrong connector, but all of these issues had no impact on assembly, as the rework was done before.

Drawing a conclusion from this, there was no possibility to reduce takt time by improving process training alone, as the issues underlying the product were driven by engineering disturbances. The entire buffer of four takts would be used up before the end of line. The solution of reengineering all parts was not feasible, as the first batch of the new products started production in less than a month.

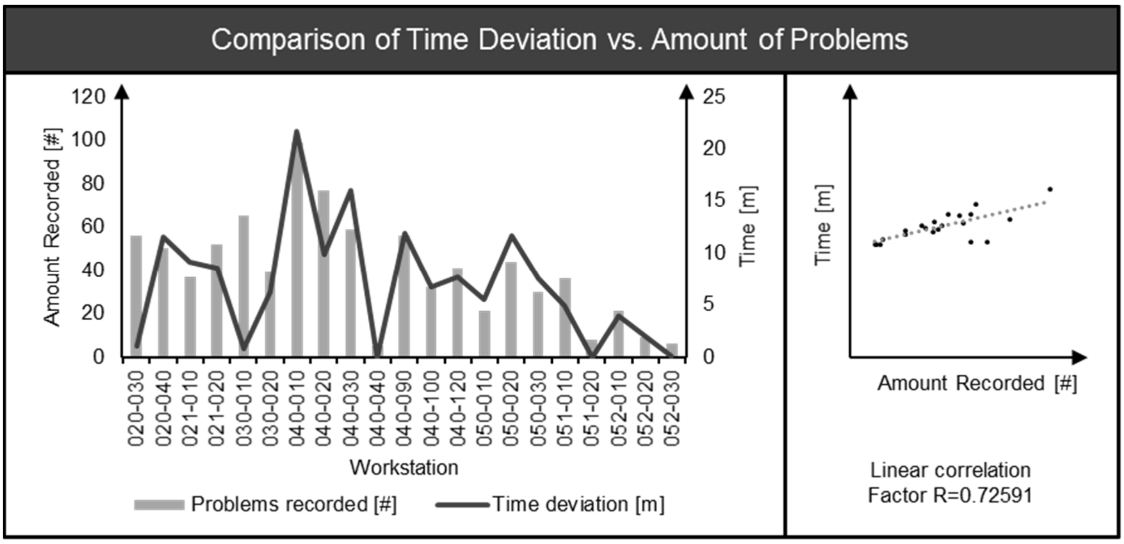


Figure 6-9 Comparison time deviation vs. problems recorded

Following up on the data gathered, an estimation for the takt times during VS1 was derived, analysing the potential impact onto the series assembly line.

Defining Main Issues and Mitigating with Quick Wins

The impact of new parts onto the assembly process is not known; therefore, this remains a potential influence point. Although reengineering parts potentially improves the assembly process, by introducing better tolerance, or similar, the impact on logistics might negate this factor. Every new part or adapted part bears the danger of being missed or wrongly delivered, or not fitting to the product and thus resulting in process disturbances. Hence, no estimation was provided based on this factor.

Process changes and process deviations were regularly observed during VS0, but their impact was already included in the takt times measured, as nearly all of them had to be applied on all cars. As these changes were necessary due to parts being out of specification, estimating their disturbances onto the assembly line was not sensible.

For the first batch of production, it was also expected that the problems recorded would remain the same and not be solved. Therefore, the impact of these adaptations could not be verified, and only a potential correlation noticed.

Having this in mind, investigation for solutions started. The first approach was to identify potentials for reducing the time by decoupling pre-assemblies with additional workers. Further discussions with the assembly team revealed next to the parts availability problems a potential tool availability issue. As shown in Figure 6-10, this left three station groups with exceeding takt time: The harness fitting stations (area I), the cockpit stations (area II) and the fitment of seats (area III). Negative times are due to the extraction of pre-assemblies, leading to an effective speed-up of the process.

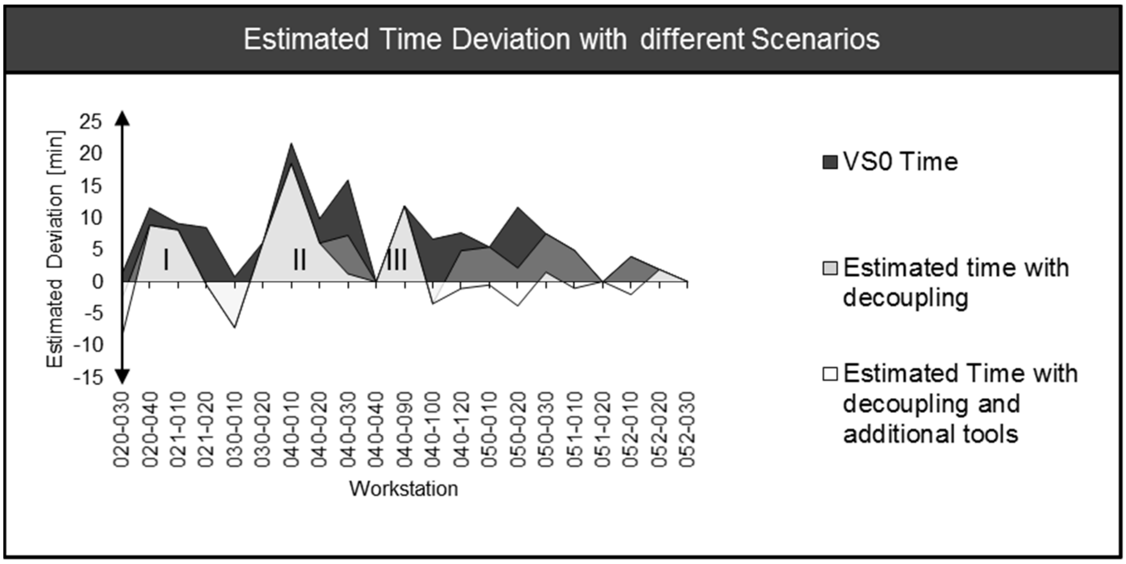


Figure 6-10 Impact of possible solutions on takt time

The seat fitting area had problems in regards to available jigs. The issue was unresolved, and only by introducing new jigs would the target be met. The cockpit fitment had its own set of issues. A completely new process and instable pre-assembly stations did not allow for adaptations. Recommendations given for all areas included decoupling, floaters and additional workers, but it was decided by management that only the wiring harness had to be dealt with. Hence, the focus was set on the station 020-030 to 021-020.

Starting with the process instructions for station 020-040, the first task was to improve the qualifications of the associates, as the process time was actually never achieved. During a three-day workshop, the associates and the assembly planner together redesigned the process work instructions. Followed up by repeated training sessions, the work time of the two associates was reduced from 19 and 15 minutes to respectively 10.5 and 10 minutes. The training was also used as a test-run for the real time monitoring, as disturbances and time keeping were manually recorded.

Various changes were adapted, ranging from the order of process steps to swapping work content between two stations. With adapting these simple changes, the workstation already had achieved a time saving of the exceedance, meaning the buffer time would not be used up if everything else was done according to plan.

Although the target time was already achieved at station 020-040, stations 021-010 and 021-020 were not stabilised, but due to time restrictions, a decision was taken that these issues will be solved during production of the first batch.

Logistics on the other hand encountered entirely different problems. During the VS0 build, many parts delivered to the line were not those actually demanded in the bill of materials. Issues such as different change index levels or missing part number labels were forcing the assembly to investigate if the parts were the correct ones, leading to lost time. Especially because of the distance to the LSP, a delay of up to one hour would result if the parts could not be taken from the following vehicle or similar. To ensure this would not happen again, logistics established a physical parts check for incoming goods. All parts that were specific for the new product were checked for quantity, quality and data consistency. As a result, over 25% of the checked parts had issues, and all of these issues were solved before. With only 12 parts awaiting delivery to the warehouse for the first car, the logistics operation board was confident in delivering all parts on time.

6.3.3 Production Control of Pre-Series 1 Batch 1

The production of pre-series 1, known as VS1, was split into two batches of production. Production of the first six cars started in late 2016 and the methodology was tested upon them. The second batch was not monitored, and measurement was performed in the same way as in VS0.

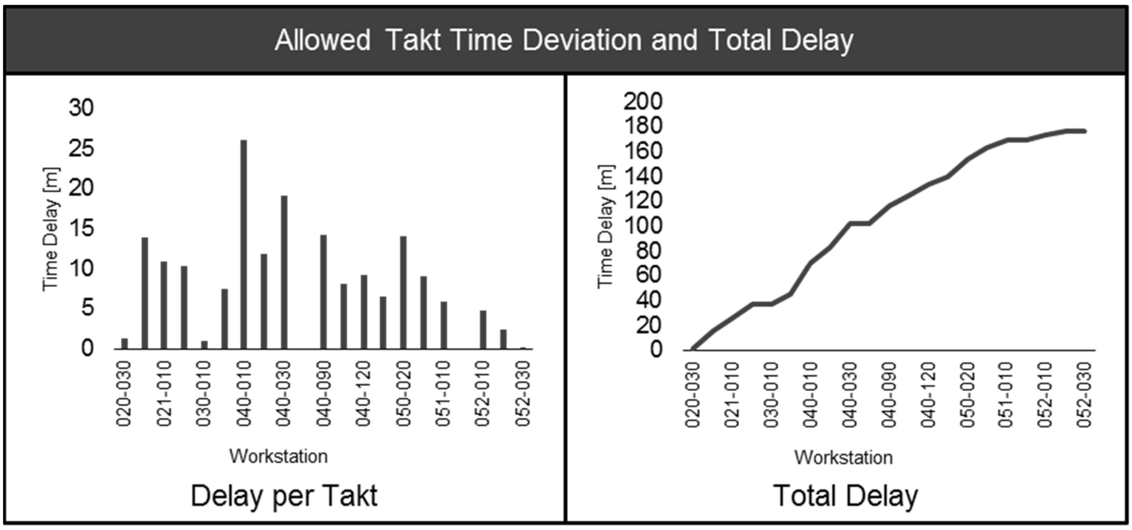


Figure 6-11 Allowed time delay per takt (left) and development per vehicle (right)

As examined in the previous chapter, the resolution was that the first four stations are the focal point of study. The changes agreed upon where implemented via the standard process. For having an overview on the delay and the resulting total delay, the takt time deviation of VS0 was extrapolated onto the four takts of the buffer, as seen in Figure 6-11. For the production of the six cars, it was estimated that the negative times as seen in Figure 6-10 would have no effect on catching up, as the VS1 production would work through breaks and eventually catch up to series production, limiting the maximum time saved, resulting in the not decreasing total delay in Figure 6-11.

The work process was supervised with a print out of the work content (example seen in the Appendix), and the sequence was observed. During the building process, the target times were monitored, eventual disturbances noted and, if necessary, the sequence was changed. Additionally, logistics set-up a "logistics helpdesk" which was steering all parts availability issues.

The monitoring of the stations is further discussed by the observed values of worker A at station 020-030 and 020-040, as they are the best showcases of the real time control. Figure 6-12 and Figure 6-13 depict the measured time split for these stations, with the "net" assembly being identified as the total assembly time minus disturbances. The disturbances are classified into five groups of loss[264]:

- Time lost due to tooling
- Time lost due to difficult fitment
- Time lost to inherent process disturbances
- Time lost due to logistics issues
- Various time losses that cannot be classified.

Both stations have seen a decrease in assembly time, but the differences observed need to be examined. Although the net assembly time of station 020-030 was already stabilised at 32 minutes after launching car two, the overall takt time has still seen variances. Time lost to tooling was highly dependent on the progress of the other associate. While both were working in parallel, if one worker had a delay, the other would have to wait for tools, as there were not enough for both. In addition to that, one of the fixtures for assembly was broken; hence, car 3 had additional process issues.

Fitment issues were closely related to the delivery process of a single part. The sound insulation for the bonnet was missing every time, and logistics were always delivering it after the takt had started. Cars 1, 3 and 5 had the sound insulation delivered before the end of the process, and the fitment of the part was performed in takt time. Due to engineering issues, the delivered insulation would always have issues during fitment. Car 2 on the other hand had completely missed the sound insulation, and it was not delivered before the work content was finished, hence there were no fitment issues recorded.

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[264] The actual time recording sheet used for WS 020-030 can be seen in Appendix I

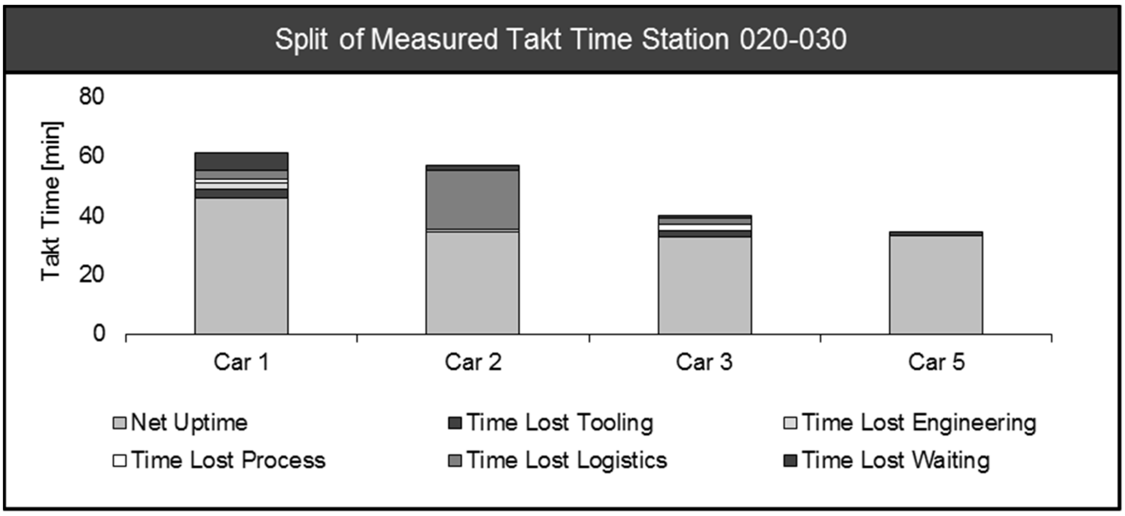

Figure 6-12 Takt time split worker A station 020-030

In conclusion, the process itself was stable, and no measures were applied, as the given takt time was adhered to.

Station 020-040 on the other hand faced different problems. As this station was set for fitting the main wiring harness, the results of the workshop and training were expected to be seen here, but change management failed to implement them.

During the workshop, a new process sequence was set up, showing effects in saving time and optimising the flow. Unfortunately, a lack of communication resulted in the associates working on the product not knowing of these changes, as they were not part of the testing team. The direct effect was a loss of ten minutes due to these changes during cars 1 and 2. After implementing the changes, the assembly time was already reduced.

Missing tools or bad tool design posed again an issue, as the associates had difficulties scanning and mounting belt retractors. Car 3 was the first car that saw the application of a floater, and therefore the time lost due to a logistics problem was mitigated. The floater was necessary, as both associates in cooperation performed the routing of the main wiring harness. Worker B had problems with an aperture needed to fit the seal of the boot, and was delayed. Therefore, it was decided that one of the already trained experts would function as a floater. With him supporting the process, five minutes where saved on cars 3 and 5, so that the takt time would not exceed too much, or in the case of car 5 not at all.

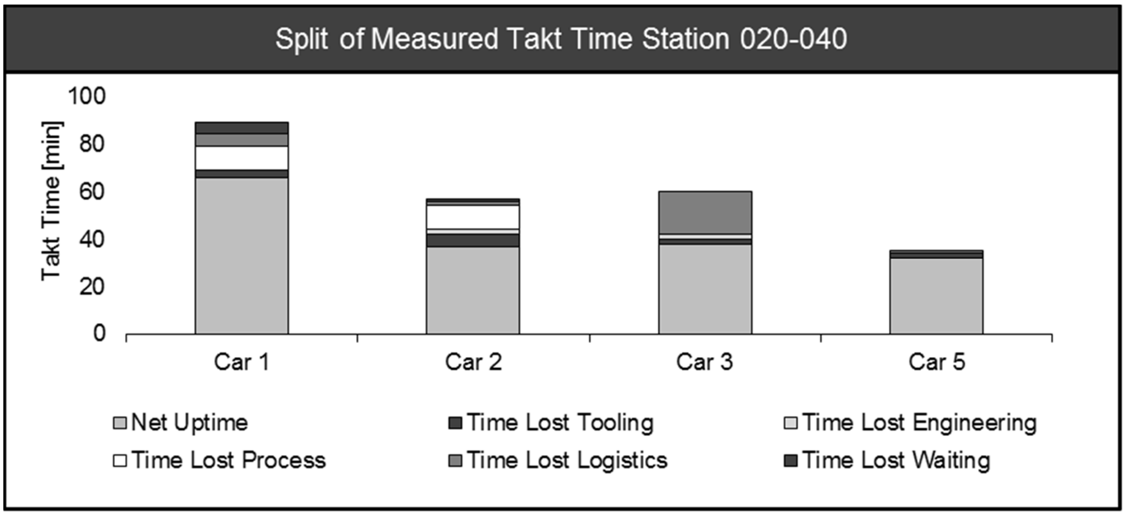

Figure 6-13 Takt time split worker A station 020-040

As an outcome of these changes applied to the two stations, after car 3 no buffer time was lost. The OEE has improved from less than 50% for the first car, to close to above 90%, with no direct disturbances left. Calculating the value added uptime, as defined in Chapter 5.8, can hence be shown for station 020-040 as depicted in Figure 6-14. By analysing every station in this way, an overall OEE for whole production line and all workstations could have been calculated, and, by means of SPC, a full stability and capability report calculated. Analysing every station in this way, problems could have been directly identified, and the overall production could have been stabilised.

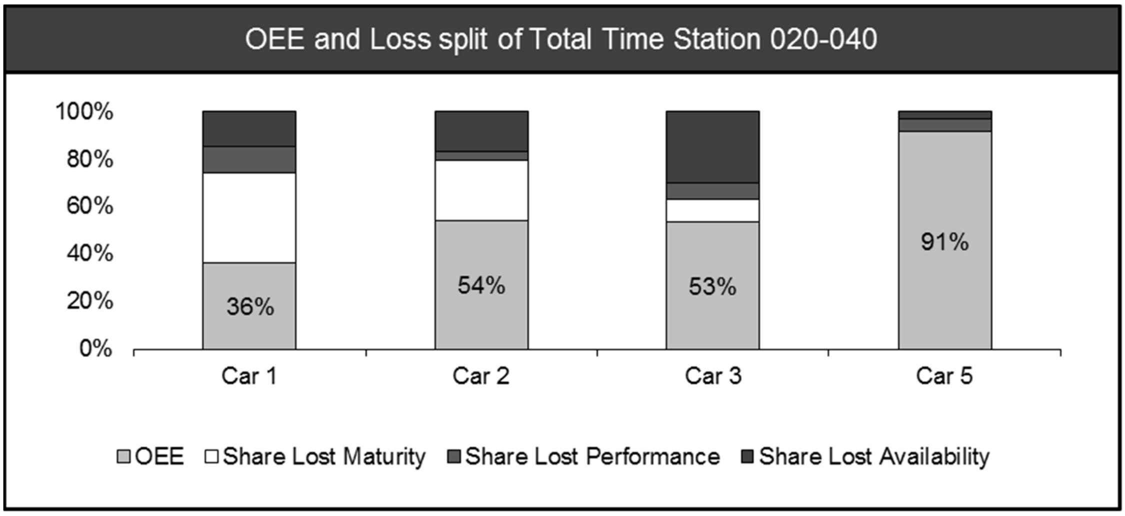

Figure 6-14 Overall equipment effectiveness of station 020-040

In contrast to the timesaving in the first stations, the entire production system went out of boundaries. The newly launched RRNM vehicles were moving ahead faster than the series production. Due to missing parts and bad fixtures for assembly, the workstations of area II and III were slowing down the entire production line. In consequence of that, the associates did not have the pressure of adhering to the takt time anymore, and the production slowed down. Per day, a planned volume loss of 5% occurred, but the management was determined not to pull a single product of the line, as the consequences would be even greater.

Suggestions for improvement were given out of the data gathered, and the effect on the second batch needed to be verified.

The effort of the logistics help desk was noticed, as the average delay in production to missing parts was reduced from seven minutes to four. An inquiry based on missed parts and new parts set-up revealed no relation. The impact of new parts onto the logistics processes cannot be confirmed therefore. Gathered data was evaluated and improvements on the helpdesk were set-up to confront issues for the second batch.

6.3.4 Production Control of Pre-Series 1 Batch 2

As the production of the second batch started towards the end of the placement, only a few observations were made, and application of the methodology was minimal.

The main changes were in the field of the logistics help desk. By having a stationary check of all parts delivered to the plant, investigation and retrieval of missing ones was performed at an earlier stage. To keep the process as smooth as possible, a second, mobile help desk was installed, that would follow the vehicle through the assembly line as it progressed.

The area formerly focused on was not controlled anymore. The takt times measured by the associates were above the times measured during VS1 P1. Possible reasons for this were newly introduced parts, some process adaptations, and the fact that there was no monitoring at all.

Additionally, the measurement of times was not comparable to the actions performed in the previous two build phases. This was mainly due to the training of additional associates, thus instead of two workers up to four were working simultaneously on the vehicle. As a conclusion, the measured times would provide no information on how the process has progressed.

6.4 Discussion of Application

Summarising the experience gathered, the methodology has a potential to stabilise the ramp-up production in a short term, especially when launching the production onto a mixed model assembly line, where series processes may not be interfered. Nevertheless, the realisation also revealed some key parameters required for the methodology to be accurate and effective.

While the implementation of the methodology to stabilise production in the first few stations was a success, the rest of the assembly line still failed to adhere to the norm. Process times exceeded regularly, and although production seemed to trend towards the target times, a stable and capable condition was never met. Hence, to ensure the stable condition on the entire line, it is paramount that data is gathered from all stations.

A second issue was the addressing of problems by management. Many of the deviations from the target time were dealt with being issues of too little tools or missing parts. Although it is true, that some deviations from the takt time were a result from those issues, the variances had other causes as well, such as lack of training or immature parts.

An emphasis is on the fact that the conditions between the phases have changed significantly. During the first build phase, pre-series 0, production had different variants on the line. The learning effects from one product to the next were low, as many changes were still applied. During the first batch of pre-series 1, all cars had nearly the same configuration, and associates were improving their knowledge quickly. During the second batch, the variants increased already. The first vehicles were again left hand wheel drive vehicles, and takt times were low as expected, but with the first introduction of right hand wheel drive disturbances increased significantly and takt times went up. Additional to that, country specific variants increased the instabilities even more, and the process level was again low.

7 Summary and Critical Reflection

The continuously increasing competition within markets and heightened consumer awareness lead to an increase in customisation and variation of products. This results in shorter life cycles, with more rapid technology introductions and steeper ramp-ups. Accompanied by instabilities in the production system and high demands towards management, the transitioning phase from product development to series production is crucial for the success of a new product and in some cases to the entire business. Customers expect high quality and short delivery times once the product is available. To achieve this, the launch of production has to be at full capacity as soon as possible, without neglecting quality. Hence, the production and process stability have to be guaranteed. This task is usually performed during pre-series builds. In high volume production large amounts of data are generated, resulting in the identification of product specific problems. Facing the same challenges as mass producers, low volume assembly systems on the other hand cannot prove their capability in the same way since they are missing the production capacity.

The methodology developed within this thesis represents a possible solution to ensure control during the entire pre-series production, while being resource efficient. Focusing on the special characteristics of low volume assembly systems, the methodology can be applied in any production system with only slight adaptations necessary.

In the first chapter, it was determined that current methodologies applied to the problem situation are not suitable for low volume production and deriving an improved approach was necessary. The theoretical context of this issue was discussed in Chapter 2. The key terms process, stability and ramp-up were introduced and additional information on the specific issues faced by low volume systems and automotive companies was provided.

Chapter 3 reviewed existing literature on state of the art approaches on the topics of stabilising ramp-up and production control. In order to assess their suitability seven demands were formulated, based on the previously mentioned theoretical discussion. The established criteria were applied to each piece of literature and compared. This analysis justified the need for additional research due to the clear research gap.

From the academic investigation three research hypotheses were devised, stated in Chapter 4. Based on this the subsequent methodology was developed. The following chapter elaborated on the methodology, giving a comprehensive guideline on how to apply it in the field. The first part relies on gathering data, which is then analysed in the second part. This allows for an increased process knowledge, which is documented in the third and final part. After the initial set-up of targets, the main issues are defined to focus resources accordingly. This is finalised in the application of real time production control during the build phases. Having defined a method for identifying potential process issues in advance, solutions to occurring problems are suggested. The last step after real time control is the transfer from newly gathered data into comprehensive lessons learnt, to improve future production.

The methodology was validated during an industrial placement at Rolls Royce Motor Cars. The initial set-up and data investigation was executed during pre-series 0 build phase. The application was closely linked to the company's databases and which therefore did not require any adjustments. Based on the gathered data, a comparison to the targets was initiated and main issues were defined. Due to management decisions, the methodology was limited to specific workstations in the assembly line. Suggestions were made between pre-series 0 and pre-series 1, which improved production. By using additional floaters and de-coupling of pre-assemblies, the process time was reduced to adhere to takt time. A further limitation to the effectiveness of the methodology was that it could not be implemented during the entire ramp-up period. Therefore, it can be concluded that the first batch of pre-series 1 production did not result in a stable process.

The implementation also revealed several fields of improvement in the methodology. One was the intensive time used for documentation of process issues. One associate would have to monitor the build the entire time, and note every deviation and disturbance. Optimisation of the first step, data gathering, during the initial phase and the production control could improve the methodology. A suggestion would be to develop an easy to use web or offline programme for associates to document process disturbances right away.

Furthermore, the ability to predict where problems will occur enables a pro-active approach towards stabilising the ramp-up phase. The possibility of predicting the problem occurrence and the effect on takt time is highly dependent on the problem recording team. By implementing the methodology into earlier stages of the build, a link between the occurring problems and takt time deviation can be made. This could help improving the overall accuracy of future predictions.

8 Appendix

020-030, Worker A, Car: #1

Seq	TVG Number	TVG Title	Time ZMD	Time in Takt	Actual Time	Start of Dist.	End of Dist.	Code
1	K 0463 006 120 A 01	MOVE VEHICLE FROM 020000 TO 020030 (ASS 1)	2:30	2:30				
2	K 5172 002 100 A 01	FIT APERTURE SEAL REAR DOOR TO BIW - LH	2:51	5:21				
3	K 5172 001 100 A 01	FIT APERTURE SEAL FRONT DOOR TO BIW - LH	2:22	7:44				
4	K 6577 002 100 A 01	SECURE CRASH SENSOR TO B PILLAR - LH	0:17	8:01				
5	K 3540 001 100 A 01	FIT ACCELERATOR PEDAL BRACKET LHD	0:39	8:39				
6	K 3433 001 140 A 01	FIT BRAKE PEDAL BRACKET TO INTERIOR BULKHEAD	0:26	9:06				
7	K 6411 001 120 A 01	FIT BRACKETS FOR EXTRA BLOWERS - LH	0:52	9:58				
8	K 5123 002 100 A 01	FIT BONNET RELEASE BOWDEN CABLE PART 1	0:20	10:18				
9	K 5148 007 140 A 01	FIT INTERIOR BULKHEAD SOUND INSULATION A1	0:40	10:58				
10	K 6411 001 100 A 01	FIT COCKPIT CENTRE PIN TO INTERIOR BULKHEAD	0:22	11:19				
11	K 5123 002 120 A 01	FIT CLIPS FOR BONNET RELEASE BOWDEN CABLE	0:12	11:31				
12	K 5171 002 110 A 01	FIT D16 PLUG TO BULKHEAD LHD	0:36	12:07				
13	K 5171 002 100 A 01	FIT D16 PLUG TO BULKHEAD RHD	0:36	12:43				
14	K 1290 003 100 A 01	FIT STEERING KNUCKLE COVER TO 2ND BULKHEAD	0:09	12:52				
15	K 6114 001 120 A 01	FIT BRACKET FOR GENERATOR CABLES TO SECOND BULKHEAD	0:10	13:02				
16	K 5148 002 200 B 01	FIT FRONT SOUND INSULATION 2ND BULKHEAD ENGINE BAY - RH	0:26	13:29				
17	K 5148 002 200 A 01	FIT FRONT SOUND INSULATION 2ND BULKHEAD ENGINE BAY - LH	0:22	13:51				
18	K 5148 002 160 A 01	FIT SOUND INSULATION TO FRONT OUTER BULKHEAD	1:17	15:08				
19	K 6431 001 120 A 01	FIT WATER DRAIN GROMMET TO ENGINE BAY FRONT - LH	0:11	15:19				
20	K 6431 001 120 B 01	FIT WATER DRAIN GROMMET TO ENGINE BAY FRONT - RH	0:11	15:29				
21	K 3110 002 140 A 01	FIT CAGE NUT FOR WISHBONE TO FRONT STRUT TOWER LH	0:13	15:43				
22	K 3110 002 140 B 01	FIT CAGE NUT FOR WISHBONE TO FRONT STRUT TOWER RH	0:13	15:56				
23	K 6166 002 120 A 01	FIT WASHER JET AND FEED LINE TO BONNET	0:24	16:20				
24	K 5148 001 100 A 01	FIT SOUND INSULATION TO BONNET	1:04	17:24				
25	K 5123 001 140 A 01	FIT RUBBER STOP TO BONNET	0:21	17:45				
26	K 5123 002 160 A 01	INSTALL LOCK UPPER PART TO BONNET	0:38	18:23				
27	K 4100 013 230 A 01	SECURE EARTH TERMINAL FIXING IN ENGINE BAY	:	18:023				
28	K 6112 015 180 A 01	SECURE BATTERY B- CABLE TO EARTH STUD BY RH BONNET HINGE LHD - RH	0:23	18:47				
29	K 6112 015 180 B 01	SECURE BATTERY B- CABLE TO EARTH STUD BY LH BONNET HINGE RHD - LH	0:23	19:10				
30	K 6161 001 100 A 01	FIT 2 BRACKETS FOR WIPER MOTOR LH/RH	1:13	20:23				
31	K 6431 001 140 A 01	FIT MICROFILTER SEALING FRAME TO INNER BULKHEAD	0:15	20:38				
32	K 6431 001 160 A 01	FIT MICROFILTER LID TO MICROFILTER SEALING FRAME	0:22	20:60				
33	K 1713 001 100 A 01	FIT COOLANT EXPANSION TANK BRACKET TO BIW	0:19	21:18				
34	K 1612 001 100 A 01	FIT BRACKET FOR FUEL LINES TO LEFT FRONT STRUT	0:12	21:031				
35	K 6411 006 100 A 01	FIT LOCK VALVE BRACKET TO 2ND BULKHEAD	0:18	21:49				
36	K 0459 004 110 A 01	IPSQ CONFIRMATION 020-030 A1	0:20	22:9				

LP : Logistics missing part
LW: Logistics wrong part delivered
PI: Waiting Time for PI
TPT: Missing Tools
TPJ: Jig not working
PQ: PQM Process
EF: Difficult Fitment
EL: Part not Locating
EM: Misalignment
ER: Faulty Release
ET: Torque Release wrong
WA: General Waiting Time

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