Informatization in Production Planning and Control

A Simulation based Evaluation of the Impacts in Flow-Shop Production Systems

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Doctoral Thesis
to achieve the university degree of
Doktor der technischen Wissenschaften
submitted to
Graz University of Technology

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Graz, January 2016

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Acknowledgement

I would like to express my gratitude to my supervisor Prof. Siegfried Vössner for his comments and remarks. Furthermore, I would like to thank my colleagues Gerald, Dietmar, Nik and Julia for the inspiring discussions. In addition, I would like to thank Herbert Steiner for his trust and the chances to apply my knowledge in several industrial projects. Also, I would like to thank my parents Ludwig and Siglinde who supported me throughout the entire study and during the process of thesis writing. My special thanks are extended to Nina for supporting me with all possible means through the scientific journey.

Christoph Wolfsgruber

Abstract

The manufacturing industry of today is coined by the increasing dynamics of the markets. Products are demanded in increasing varieties, the product life cycles are getting shorter and demands fluctuate more and more. These trends are pushing the complexity in production planning and control to new levels. However, the future also offers new promising opportunity. The informatization in manufacturing has reached after 40 years of the first computer integrated manufacturing concepts the shop floor. Internet of things and cyber physical systems are seen as the enabling technologies behind the visionary concept of Industry 4.0. These technologies will change the production planning and control in many ways. Data quality will increase dramatically, status updates from the shop floor and the tracking of all activities and objects will be available in real time.

These developments lead to the request of the evaluation of different production planning and control methods regarding the challenges and opportunities of these developments. This thesis presents a simulation based evaluation study which analyzes the impacts of informatization in production planning and control in flow-shop production systems of automotive industry. Especially the relationships between data quality and planning model accuracy with respect to the requested product flexibility is analyzed in this doctoral thesis. Based on the found insights, a best practice approach for the optimal configuration of a production planning and control system is deduced.

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1 CHAPTER

Introduction

It is not the strongest of the species that survives, nor the most intelligent, but rather the one most adaptable to change.
Charles Darwin (1809 – 1882)

Already 500 years before Christ Heraclitus[1] claimed "*nothing endures but change*" and the change itself seems to have gathered more momentum in the recent years. Industrial production companies are operating nowadays in an extremely turbulent environment (Westkämper & Zahn, 2009; Nyhuis, et al., 2008). This environment is characterized by the rapid spread of new technologies, new often very offensive competitors, and ever tighter supply chain network. Products are demanded in increasing model varieties, the product life cycles are getting shorter and demands fluctuate more and more. In order to maintain the competitiveness, companies must be able to respond to these turbulences quickly and flexible (Nyhuis, et al., 2008). As the main focus of this thesis is in the automotive industry, an overview of ongoing mega trends in that industry sector is given. Next, the motivation as well as the gaps for this thesis are described. In the last section of this chapter the research question, the focus and the used research methodology is defined.

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[1] Heraclitus of Ephesus (535 BC – 475 BC) was a Greek philosopher who is famous for his insistence on ever-present change in the universe

1.1 Industrial Trends

The developments in manufacturing especially in automotive industry show three major ongoing trends over the past years, which will have significant impact on the future global production structures (Krog & Statkevich, 2008; KPMG, 2010; McKinsey & Company, 2013; Plattform Industrie 4.0, 2013; International Data Corporation, 2014):

Trend 1: Increasing competitive pressure and globalization

Trend 2: Individualization of products

Trend 3: Informatization of production

1.1.1 Increasing competitive pressure and globalization

The global market and competitive structures have changed fundamentally in recent years. There is an ongoing trend of consolidation in the automotive industry. A study of KPMG (2010) shows the development of the brands in the European automotive industry (see Figure 1.1). The number of individual brands in Europe declined from 70 in the 1960s to six in 2010.

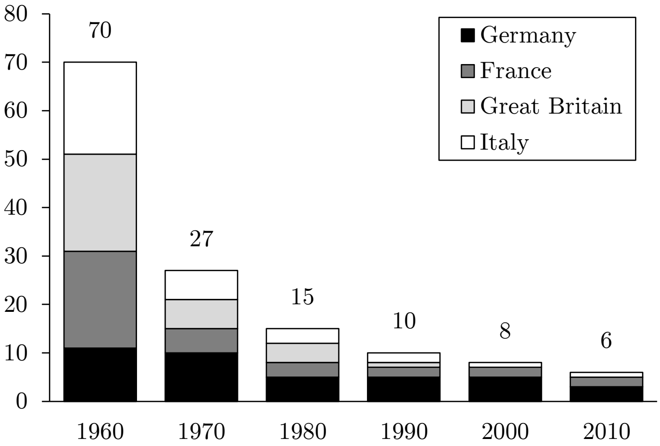

Figure 1.1: Brand concentration in the European automotive industry[2]

The merging of the companies leads on the one hand to a strong competition with each other, and on the other hand to growing sizes of companies whose factory

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[2] Data from a study of KPMG (2010).
Germany 2010: BMW, Mercedes Benz, VW (not including brands of US manufacturers)
France 2010: PSA, Renault(-Nissan)
Great Britain 2010: no manufacturer (Rover is since 2005 part of Tata)
Italy 2010: Fiat

networks are stronger and more complexly linked together (KPMG, 2010). The overall strategic objectives, the production at highest possible yield with given resources (resource productivity) and the lowest use of resources for a given production volume (resource efficiency) will also stay the same in future (Plattform Industrie 4.0, 2013). To master the complexity of highly interconnected production networks that operate at peak productivity, the need for development in the area of production planning and control is obvious.

1.1.2 Individualization of products

The value creation process of any organization is based primarily on the fulfillment of customer needs. Since the last years, the automotive market is dominated by the continuing trend of mass customization. Customers of today do not want standard products, they expect vehicles that exactly match their individual needs and desires (Holweg & Pil, 2004).

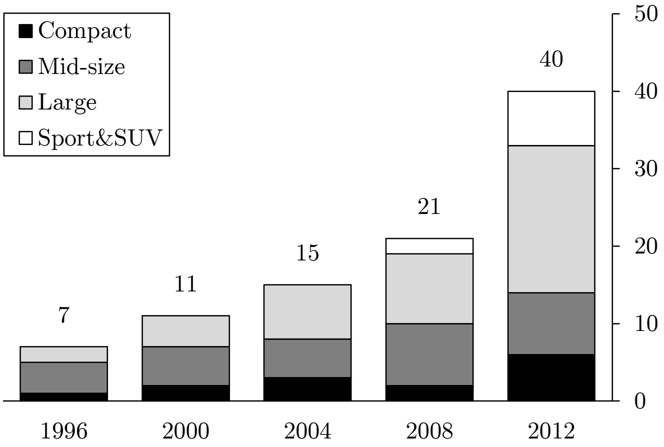

Figure 1.2: Development of the model range of Audi[3]

Figure 1.2 shows the development of the model range of Audi. The number of car models at Audi exploded from 7 in 1996 to 40 in 2012. Although this development is quite remarkable, Audi is just one of twelve brands of the Volkswagen Group[4]. Through the customer's demand for strong expression of individuality, the manufacturers need to offer a more targeted, varied product portfolio. However, even if the individual derivatives are based on a single platform, the growing product number drives complexity in production (McKinsey & Company, 2013).

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[3] Data of 1996 – 2008 from Krog & Statkevich (2008), 2012 from the webpage of Audi (2012)
Compact: A1, A2, A3; Mid-size: A4, TT; Large: A5, A6, A7, A8; Sport&SUV: R, Q

[4] In 2014, the Volkswagen Group comprises twelve brands from seven European countries: Volkswagen Passenger Cars, Audi, SEAT, ŠKODA, Bentley, Bugatti, Lamborghini, Porsche, Ducati, Volkswagen Commercial Vehicles, Scania and MAN.

An additional aspect in the individualization of products are the changing regional and segment patterns to which the car manufacturers have to adapt their production supply chains, and portfolios. McKinsey & Company (2013) claim "*…the potential for portfolio mis-match as smaller vehicle classes are growing more strongly than others in fast-growing emerging markets.*"

In order to maintain the competitiveness, companies must offer an increasing number of varieties, which also leads to a higher fluctuation of demands and diverse product mixes. Operating in such a turbulent environment demands from companies of today to be able to quickly and flexible respond to these turbulences.

1.1.3 Informatization of production

The rise of internet connections, storage capacities and computation power in an exponential way over the last years is not expected to decline. The International Data Corporation (IDC) estimated the digital universe[5] in the year 2013 by 4.4 zettabyte[6] and is expecting a rise to 44 zettabyte in the year 2020 (International Data Corporation, 2014). The connection of physical things via the internet called Internet of Things (IoT) will contribute an increasingly large share to the digital universe. According to the IDC (2014) 2% of the world wide digital universe was generated by IoT embedded systems in 2013 and they expect that this share will rise beyond 10% in 2020. The real time availability of information will lead to more efficient and intelligent operations. One concept which is driving the informatization of production is the future project of the German high-tech strategy called Industry 4.0, which promotes the computerization of manufacturing. IoT, mobile internet, automation of knowledge work and advanced robotics is seen as the potentially disruptive technologies related to Industry 4.0 (McKinsey & Company, 2014). Also the horizontal and vertical system integration, simulation and large scale data analytics are seen as the technologies that will transform industrial production (Boston Consulting Group, 2015). Overall, these technologies will also have major impacts on the ways production is planned and controlled.

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[5] The digital universe is a measure of all the digital data created, replicated, and consumed in a single year.

[6] 1 zettabyte equals 10^{21} byte

1.2 Motivation

The above described trends have a considerable influence on the supply chain management (SCM) of today's companies. Driven by the increasing competitive pressure, it is a must for companies to operate their supply chain optimally. However, the huge complexity of modern globalized manufacturing networks, or even single production sides with a high number of individualized products is forcing companies to make compromises. Nowadays most manufacturer optimize locally using simple planning models with data which are often of poor quality. Ten years ago Deloitte (2003) claimed this optimization paradox as one of the critical trends driven by complexity.

> *Despite the potentially huge economies from designing supply chains from a global view, most manufacturers optimize locally. Manufacturers are spreading supply chain operations across the world. Yet, most still appear to be optimizing their supply chains on a "local" basis – by product, function (say, production), facility, country, or region. This means they are losing opportunities for large-scale efficiencies. (Deloitte, 2003)*

Nowadays, the situation looks the same. The major reason for this optimization paradox are the missing mathematical tools for production planning. Already 50 years ago Conway et al. (1967) stated the frustrating complexity of the so called job shop problem, which describes the assignment of jobs to resources at particular times.

> *The general job shop problem is a fascinating challenge. Although it is easy to state, and to visualize what is required, it is extremely difficult to make any progress whatever toward a solution. Many proficient people have considered the problem, and all have come away essentially empty-handed. Since this frustration is not reported in literature, the problem continues to attract investigators, who just cannot believe that a problem so simply structured can be so difficult until they have tried it. (Conway, et al., 1967)*

Now, 50 years later, branch-and-bound algorithms, constraint programming and heuristic optimization methods can solve slightly bigger problems but there was no fundamental breakthrough. Only for the individual areas of production planning, concepts and methods exist such as lot sizing, master planning, etc. but there is no comprehensive, holistic solution. Furthermore, the models these methods are using are based on simplifications of some sort, because the real world is too complex to analyze directly (Hopp & Spearman, 2008). However, the new possibilities of computation offer some promising results. Agent based computation and real time availability of data will play a major role in the next generation of production planning and control methods. Also in Industry 4.0, the following research recommendations are stated to tackle the optimization paradox of production planning (Plattform Industrie 4.0, 2013):

- Development of methods and concepts to increase resource efficiency by viewing the overall optimum.
- Development of new strategies and algorithms which fulfill the need for higher flexibility. This includes optimized planning and control strategies for adaptable production systems.

The vision of Industry 4.0 is an intelligent planning and control system based on a continuous real-time simulation that automatically is rescheduling the production based on the requirements and the available resources. This vision is also shared by Schenk et al. (2013) and Nyhuis et al. (2008).

In addition to that vision, many other literature sources describe gaps in the theory of production planning. Krishnamurthy et al. (2004) stated the lack of quantitative studies that analyzes the performance of material control strategies in manufacturing environments with multiple products and diverse product mixes. Jodlbauer & Huber (2008) recommend research in the robustness and stability of production planning and control strategies in complex job-shop environments or real-world applications.

An even almost open field in theory is the added value of high quality data in production planning. Recently, the impact of inventory inaccuracy in SCM were analyzed (Fleisch & Tellkamp, 2005) but there is still only limited amount of research on the effects of informatization on PPC available.

This all leads to the motivation of research in the field of production planning under the perspective of the need of more flexible production systems due to the increasing complexity driven. Thereby also the promising new possibilities due to informatization and their impacts on the performance of the production system are of interest.

1.3 Research Question

Based on the above described industry trends, as well as the gaps in literature, this thesis deals with the question of which production planning and control method allow the efficient production of mass customized products under the use of new opportunities through the ongoing informatization in manufacturing.

Due to different industry and production process properties it is necessary to focus on a clearly defined domain for answering this question in-detail. Driven through the experience of several industrial projects the selected focus domain is the supply industry of automotive production.

To specify this focus in more detail, the process product matrix of Hayes & Wheelwright (1979) is used, which classifies manufacturing environments by their process structure into four categories (Hopp & Spearman, 2008):

- Job shop: Small lots are produced with high variety of routings through the plant. The flow through the plant is jumbled and setups are common.
- Disconnected flow lines: Product batches are produced on a limited number of identifiable paths through the plant. The individual stations within a path are not connected by a material handling system, so that inventory can build up between stations.
- Connected line flow: The product is fabricated and assembled along a rigid routing connected by a material handling system. This is the classical moving assembly line made famous by Henry Ford[7].
- Continuous flow process: The product (food, chemicals, etc.) flows automatically down a fixed routing.

In the supply industry of mechanical products in automotive industry, the prevalent manufacturing environment is the discrete part production in batches on disconnected flow lines (see Figure 1.3). Therefore, the primary perspective of this thesis lies in such an environment. Typically, the two contrary production planning and control principles push and pull are used in this area. Especially on the push side, a variety of different approaches using various levels of modeling detail exist. Moreover, push type methods are very depending on the availability and quality of data. This thesis should give an answer on the question of the required detail of the decision model used in production planning depending on the level of informatization. Moreover, a

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[7] Henry Ford (1863 – 1947) was an American industrialist, the founder of the Ford Motor Company, and sponsor of the development of the assembly line technique of mass production, which he was successfully applied in the production of the famous car Model T.

comparison of push and pull type methods should show the advantages of the divergent approaches for different manufacturing settings.

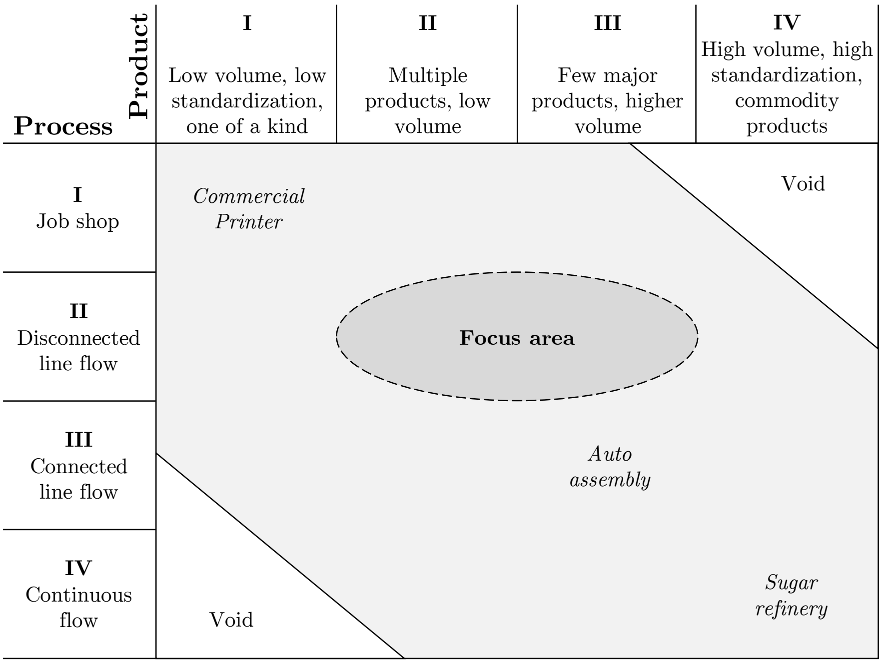

Figure 1.3: Process focus area of the thesis[8]

Considering the motivation and the focus of this thesis, the research question is the following:

Question: *What is the optimal production planning and control configuration for a discrete part production in batches in a disconnected flow line in the environment of automotive supply industry under the perspectives of a higher need of flexibility due to individualization of products and the increasing level of informatization of production systems?*

To answer this question a detailed understanding of the production relationships and the existing concepts and methods of production planning is needed. In order to make a quantitative statement a simulation model based approach is needed to evaluate the performance of different planning and control approaches for various production settings. Moreover, using such a model, settings which are nowadays in reality not possible can be simulated and the potentials of these settings can be investigated.

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[8] adapted from the product process matrix (Hayes & Wheelwright, 1979)

1.4 Research Methodology

In this thesis a simulation approach is used to develop a theory that gives an answer on the above stated research question. Especially in the area of production and operational management (POM) and operational research (OR) simulation is a key technique for science. Davis et al. (2007) describe the increasingly significant methodological approach of simulation for the development of theory.

> *Simulation can provide superior insight into complex theoretical relationships among constructs, especially when challenging empirical data limitations exist. (Davis, et al., 2007)*

Davis et al. (2007) suggest the following roadmap which is also used in this thesis:

1. Determine a theoretically intriguing research question
2. Identify simple theory that addresses the research question
3. Choose simulation approach that fits with research question, assumptions, and theoretical logic
4. Create computational representation
5. Verify computational representation
6. Experiment to build novel theory
7. Validate with empirical data

Thereby the research process begins with the formulation of a research question (1) on a theoretically relevant issue. In the next step (2) the relevant simple theory is identified and theoretical logic, propositions, constructs, and assumptions are used to form the basis of the computational representation. By simple theory, Davis et al. (2007) mean *"undeveloped theory ... which includes basic processes that may be known but that have interactions that are only vaguely understood, if at all".* Before the creation of the simulation model, the roadmap suggests to select an appropriate simulation approach (3) that fits with the research question, assumptions, and theoretical logic. The central activity in the research process is the creation of the computational representation (4). According to Davis et al. (2007) this activity involves *"(a) operationalizing the theoretical constructs, (b) building the algorithms that mirror the theoretical logic of the focal theory, and (c) specifying assumptions that bound the theory and results".* The verification of the computational representation (5) confirms the accuracy and the robustness of the computational representation as well as the internal validity of the theory. The experiment step (6) is the heart of the roadmap for developing the novel theory. There are several approaches for effective experimentation: (a) varying value that were held constant in the initial simple theory, (b) breaking a single construct into constituent component constructs, (c) varying assumptions and (d) adding new features to the computational representation. The final step in theory development using simulation methods is validation (7), which involves the comparison of simulation results with empirical data.

Applying this roadmap on the research question leads to the following approach (see also Figure 1.4).

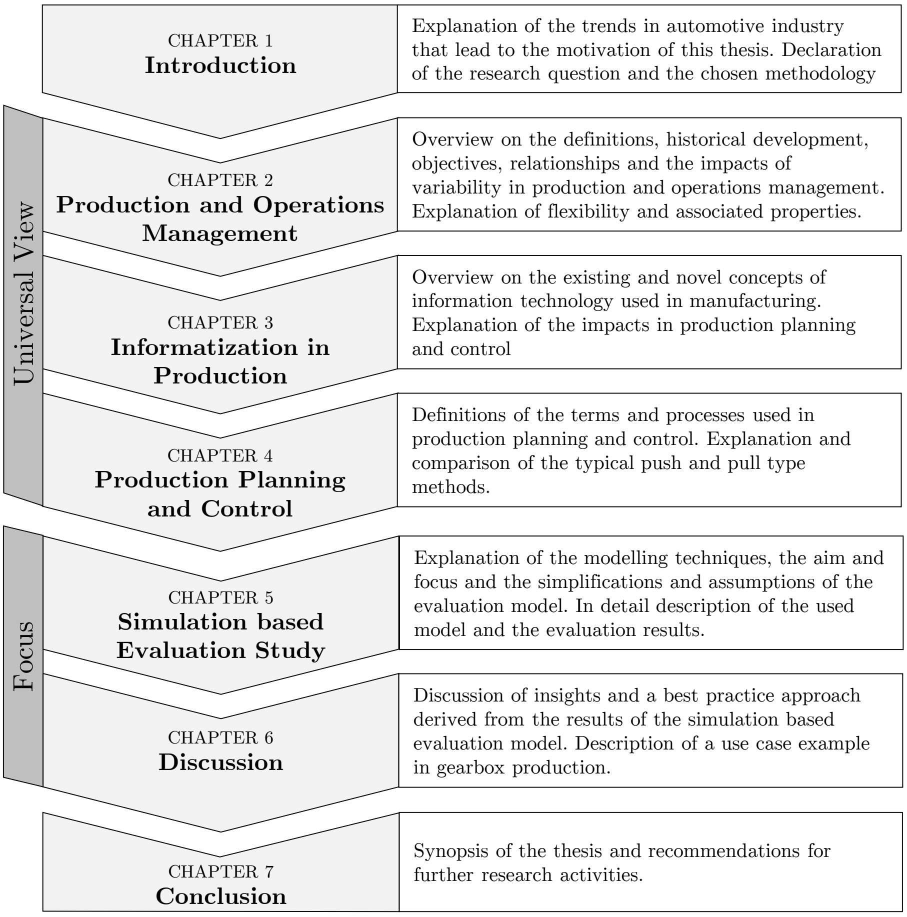

Figure 1.4: Overview of the approach of this thesis

Having already defined the research question in this chapter the identification of the simple theory is the next step. Therefore, in Chapter 2, the main objectives and relationships in production and operations management are identified. Next in Chapter 3, the new prospects of informatization and their impacts to production planning are investigated. Following, in Chapter 4, the state of the art production planning and control methods are analyzed and a comparison between the different approaches is made. Having addressed the existing theory in general, a simulation based evaluation study is presented for the selected focus domain (Chapter 5). In this chapter, the modelling approach with the used techniques, the aim and focus and the simplifications and assumptions are explained. Furthermore, the implemented computational representation is explained in-detail. Thereby the used production model, the customer model, as well as the used planning methods get described. Also the results of the various simulation experiments are shown in this chapter. The suggested validation of the simulation results with empirical data is not made in this study for the following reason: According to Davis et al. (2007) validation is less important *"...if the theory is based on empirical evidence (e.g., field—based case studies and empirically grounded processes*)" for then the theory already has some external validation. Therefore, in the simulation model of this study no additional validation is needed because grounded production models and planning methods are used. The investigated novel theory is then discussed in Chapter 6. Furthermore, a use case example in the automotive gearbox production is given in this chapter. Finally, in the conclusion, a synopsis of the found insights and recommendations for further research activities are given.

2

CHAPTER

Production and Operations Management

There is nothing so useless as doing efficiently
that which should not be done at all.
Peter F. Drucker (1909 – 2005)

This chapter deals with the basic definitions and gives an overview of the historical development of management in production. Furthermore, the ongoing developments and hypes in this science field are discussed. Next, the strategic objectives of an operation are explained and broken down to operational objectives. Thereby, the conflicting operational target and the basic relationships between them are explained. Also the different types and influences of variability on the operational targets are shown. Based on these insights, the classical ways to tackle variability, flexibility and its associated concepts and different structural concepts between the various flexibility dimensions are discussed.

2.1 Definitions

Definitions form the basic building blocks for each science. This chapter provides definitions of the term "production and operations management" and also of the term "logistics".

2.1.1 Production and Operations Management

A manufacturing operation is characterized by tangible outputs (products) of manufacturing conversation processes with no customer participation whereas a service operation is characterized by intangible outputs in which customers participate and consume immediately. Typically, service operations use more labor and less equipment than manufacturing operations. (Kumar & Suresh, 2008)

In literature the term production and operations management (POM) is often used for both types, manufacturing and service operations. The term production management originates from Frederick W. Taylor[9] and became accepted around the 1930s. With the shift to the service sector in the 1970s the new name operations management emerged (Kumar & Suresh, 2008). The American Production and Inventory Control Society (APICS) defines POM in their dictionary by *"managing an organization's production of goods or services"* and *"managing the process of taking inputs and creating outputs"* (2013). Furthermore, operations management is defined by APICS as *"the planning, scheduling, and control of the activities that transform inputs into finished goods and services"* while production management is defined as *"the planning, scheduling, execution, and control of the process of converting inputs into finished goods."* (2013).

POM distinguishes itself from other functions such as personnel, marketing, finance, etc. Following are the activities which are listed under POM functions: location of facilities, plant layouts and material handling, product design, process design, production and planning control, quality control, materials management, maintenance management (Kumar & Suresh, 2008). Material handling, production planning and control, and material management can also be summarized under the term logistics which is mainly used in German-speaking Europe.

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[9] Frederick Winslow Taylor (1856 – 1915) was an American mechanical engineer who sought to improve industrial efficiency. He was one of the first management consultants and also an athlete who competed nationally in tennis and golf. (see also Chapter 0)

2.1.2 Logistics

The literature offers a variety of definitions for to term logistics. The Encyclopedia Britannica defines logistics as "*…the organized movement of materials and, sometimes, people.*" (Encyclopedia Britannica, 2014). The Council of Logistics Management, a trade organization based in the United States, defines logistics as: "*…the process of planning, implementing, and controlling the efficient, effective flow and storage of goods, services, and related information from point of origin to point of consumption for the purpose of conforming to customer requirements.*" (Encyclopedia Britannica, 2014). The term logistics is used in literature in the United States since 1950 and in Germany since 1970. From the time on a wide spread and rapidly growing importance can be found. Almost every industrial company has departments or a director position for logistics and a growing number of companies are offering logistics services. Within most of the definitions the following common elements are included (Arnold, et al., 2003):

- Logistic processes are all transport and storage processes and the associated loading and unloading, storage and retrieval and the picking.
- Logistic objects are either physical goods, in particular materials and products in the industrial company, people or information.

A logistic system is intended to carry out a variety of logistical processes. It has the structure of a network that consists of nodes, such as the inventory points (storage locations), and connecting lines between the nodes, such as the transport paths. The processes in the logistic system form a flow in the network. The supply chain is the logistics system of an industrial company. It encompasses the entire flow of goods from the suppliers to the company, within the company and from there to the customer. It can be represented as a sequence of transport, warehousing and production processes. (Arnold, et al., 2003)

According to Arnold et al. (2003) the logistic processes along a supply chain can be classified in the following way (see also Figure 2.1):

- Procurement logistics concern the flow of goods from the supplier to the raw material inventory point. This includes activities such as market research, requirements planning, make-or-buy decisions, supplier management, ordering, and order controlling.
- Production logistics connect procurement to distribution logistics. Its main function is to use available production capacities to produce the products needed in distribution logistics. Production logistics activities are related to organizational concepts, layout planning, production planning, and control.

- Distribution logistics deal with the delivery of the finished products to the customer. It consists of order processing, warehousing, and transportation.

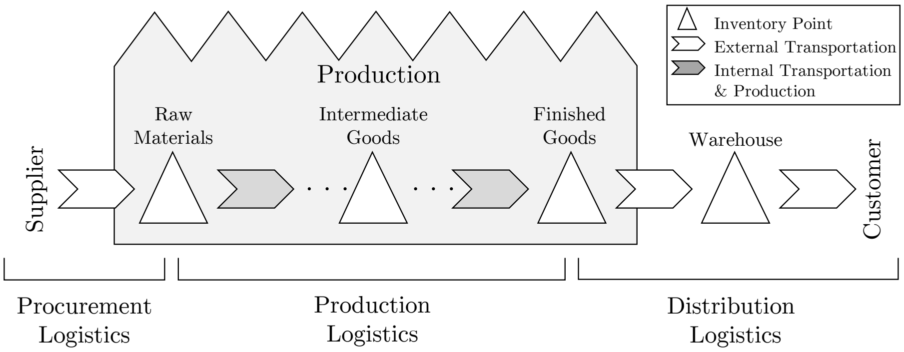

Figure 2.1: Classical logistics classification along the supply chain[10]

In addition to the flow of goods in the supply chain, the waste disposal is also a main matter of corporate logistics. Disposal logistics has the disposal of waste produced during the operation of a business as its main function. At all stages of the supply chain waste, such as production residue or packaging, can arise. That waste needs to be eliminated or fed to the exploitation in any other company or in its own production. In the latter case a backwards material flow results which is called reverse logistics. (Arnold, et al., 2003)

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[10] based on (Arnold, et al., 2003)

2.2 Milestones and Hypes

This chapter deals with the history development of POM and the ongoing trends. Similar to other science disciplines the development of POM is coined by milestones and hypes that changed the way production management has been done. Understanding this development is crucial to analyzing existing production systems and finding ways to improve them.

2.2.1 Historical Milestones

First Industrial Revolution

For time immemorial, products were made to fulfill the needs of society. In the early days these products met on an individual basis. Prior to the first industrial revolution, skilled craftsmen made products customized to individual needs, in small-scale, for limited markets and labor rather than capital intensive. (Hopp & Spearman, 2008)

In the mid-18th century several innovations appeared that helped to mechanize many of the traditional manual operations and to perform standard tasks at a faster and more effective pace. The single most important innovation of this first industrial revolution, was the steam engine, developed by James Watt[11] in 1765. Furthermore, Adam Smith[12] proclaimed the end of the old mercantilist system and the beginning of the modern capitalism in his Wealth of Nations in 1776, in which he articulated the benefit of the division of labor (Hopp & Spearman, 2008). He proposed that the production process should be broken down into small tasks, which should be performed by different workers. Through the work on limited repetitive tasks, the worker would specialize and productivity will improve. According to Hopp & Spearman (2008) *"...Adam Smith and James Watt did more to change the world around them than anyone else in their period of history".*

In 1798 Eli Whitney[13] proved that the usage of interchangeable parts is a sound industrial practice. The production of first of all firearms and then also other goods which were custom made one at a time shifted to a volume production

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[11] James Watt (1736 –1819) was a Scottish inventor and mechanical engineer whose improvements to the steam engine were fundamental to the changes brought by the Industrial Revolution.

[12] Adam Smith (1723 – 1790) was a Scottish moral philosopher and a pioneer of political economy. Smith is still among the most influential thinkers in the field of economics today.

[13] Eli Whitney (1765 – 1825) was an American inventor also known for inventing the cotton gin.

of standardized parts. This development also stimulated the needs for measurements and quality inspections. (Hopp & Spearman, 2008)

The centralized power sources of the first industrial revolution also made new organizational structures viable. At that time foreman ruled their shops, coordinating all of the activities needed for the limited number of products for which they were responsible. Production planning and control also started simple. According to Herrmann (2006) *"Schedules, when used at all, listed only when work on an order should begin or when the order is due. They didn't provide any information about how long the total order should take or about the time required for the individual operations".*

Second Industrial Revolution

Throughout the 1800s, there were many technological advances, but management theory and practice were almost non-existent. In the USA the build of the railroads ignited the second industrial revolution for the following three reasons. First for the complex operations required large-scale management hierarchies and modern accounting practices. Second, their construction created a large market for mass-production products and third, they connected the country with an all-weather transportation. Also, other industries followed the trend of the railroads towards big-business through horizontal and vertical integration. This made the USA to the land of big business by the beginning of the 20th century. Mass production of mechanical products based on new methods for fabrication and assembly of interchangeable parts was full in swing, but it remained for Henry Ford[14] to enable the high-speed mass production of complex mechanical products with his innovation of the moving assembly line. (Hopp & Spearman, 2008)

Ford recognized the importance of throughput velocity and sought to bring the products to the worker in a nonstop, continuous stream.

> *The thing is to keep everting in motion and take the work to the man and not the man to the work. That is the real principle of our production, and conveyors are only one of many means to an end. (Ford, 1926)*

Ford focused on continual improvement of a single model and pushed the mass production to new limits. He believed in a perfectible product and never valued the need of bringing new products to the market. His famous statement that *"the*

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[14] Henry Ford (1863 –1947) was an American industrialist, the founder of the Ford Motor Company, and sponsor of the development of the assembly line technique of mass production, which he successfully applied in the production of the famous car Model T.

customer can have any color as long as it's black" also shows that (Ford, 1926). Ford failed to see the potential of producing a variety of end products from a common set of standardized parts. His focus on speed motivated his moving assembly line but his concern was even far beyond assembly. Ford claimed that *"Our finished inventory is all in transit. So is most of our raw material inventory"* (1926). His company could take ore from a mine and produce a car in only 81 hours. Moreover, Ford used many methods of the newly emerging discipline of scientific management. (Hopp & Spearman, 2004)

Scientific Management

In the early 1900s, Frederick W. Taylor[15] propounded the concept of scientific management. As Whitney had made standardized material units and made them interchangeable, Taylor tried to do the same for work units by applying work standards. According to Drucker (1954) Taylor's system *"...may well be the most powerful as well as the most lasting contribution America has made to Western through since the Federalist Paper."*.

He maintained that there was a best method of performing a task which could be identified through observation, measurement and analysis. He was of the view that workers must perform tasks in a specified manner in order to improve productivity and standards must be laid down for the amount of work to be performed in a day. His philosophy assumed that workers are motivated by economic considerations and economic incentives such as different rates of pay. Beside time studies and incentive systems Taylor proposed also a system of functional foremanship in which the traditional single foreman is replaced by different supervisors, each responsible for different specific function such as quality of work, machine setup, machine speeds, maintenance, routing, scheduling and also time recording. (Hopp & Spearman, 2008)

Taylor's biggest contribution to POM was the clear separation of the jobs of management who should do the planning, from those of the workers who should work. He even placed the activities of planning and doing in entirely separated jobs. All planning activities rested within the management, while workers were expected to carry out their task in the manner determined by the management (Hopp & Spearman, 2008). However, such a removal of the responsibility from the workers causes a negative effect on quality (Juran, 1992). Furthermore,

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[15] Frederick Winslow Taylor (1856 –1915) was an American mechanical engineer who sought to improve industrial efficiency. He was one of the first management consultants and also an athlete who competed nationally in tennis and golf.

Taylor's reduction of work task to their simplest components could cause negative effects on the productivity on the long time and make workers inflexible. In contrast the Japanese, with their holistic perspective, quality circles, suggestion programs and worker empowerment practices legalize planning on the part of the worker and encourage their workforce to be more flexible.

One of Taylor's collaborators was Henry L. Gantt[16], who created innovative charts for production control. According to APICS, a Gantt chart is *"the earliest and best known type of control chart especially designed to show graphically the relationship between planned production and actual performance."* (2013).

Gantt (1919) gives two principles for his charts, which are still used by modern project management software:

- Measure activities by the amount of time needed to complete them
- The space on the chart can be used to represent the amount of the activity that should have been done in that time

He described several different types of charts on which Clark (1942) provides an excellent overview. The so called daily balance of work shows the amount of work to be done and the amount that is done and serves as a method of scheduling. Gantt's man's record and machine record charts are used to record past's performance and also track reasons for inefficiency. Beside those he also developed layout charts, progress charts, schedule charts, order charts and so on. In conclusion it can be said that Gantt was a pioneer in developing graphical ways to visualize schedules and shop status (Herrmann, 2006).

Beside Taylor and Gantt there were also other pioneers of scientific management. The most prominent among these were Frank[17] and Lillian Gilbreth[18]. They extended Taylors time study to what they called motion study, in which they made detailed analysis of motion involving bricklaying in the search of a more effective procedure. They were also the first that applied motion picture cameras for analyzing human motions, which they categorized into 18 basic components. (Hopp & Spearman, 2008)

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[16] Henry Laurence Gantt (1861 – 1919) was an American mechanical engineer and management consultant who is best known for developing the Gantt chart in the 1910s.

[17] Frank Bunker Gilbreth (1868 – 1924) was an American early advocate of scientific management and a pioneer of motion study. He is also known as the father in the book Cheaper by the Dozen and Belles which tells the story of their family life with their twelve children, and describes how they applied their interest in time and motion study to the organization and daily activities of such a large family.

[18] Lillian Evelyn Moller Gilbreth (1878 – 1972) was an American psychologist and industrial engineer. She was together with her husband efficiency experts who contributed to the study of industrial engineering in fields such as motion study and human factors.

Organization and Management Science

In the interwar period family control of large-scale, vertically integrated manufacturing enterprises was still common. Further organizational growth would require the development of institutional structures and management procedures for controlling the resulting organizations to take advantage of the economy of scope. (Hopp & Spearman, 2008)

This period was strongly influenced by Pierre S. Du Pont[19], who was well aware of scientific management principles. Together with his associates, they installed Taylor's manufacturing control techniques and accounting system and also introduced psychological testing for personal selection. His most influencing innovation was the refined use of return on investment (ROI) to evaluate the performance of departments. (Hopp & Spearman, 2008)

Together with Alfred P. Sloan[20] at General Motors, they planned to structure the company as a collection of autonomous operation division coordinated but not run by a strong general office. The various divisions were carefully targeted at specific market in accordance with Sloan's goal of *"a car for every purse and purpose"* (1924). This strategy was stunningly effective, while Ford was still producing the Model T. Together Sloan and Du Pont shaped the structure of modern manufacturing organization. Even today, companies with a single line of product for a single market use a centralized, function department organization, while companies with several product lines or markets use the multidivisional, decentralized structure developed at General Motors. (Hopp & Spearman, 2008)

This period also saw the development of the human relation movement. Elton Mayo carried out the famous Hawthorn studies and concluded that productivity was not affected by the environment alone (Hopp & Spearman, 2008). Worker motivation has an important part to play which lead to the development of motivation theories by Maslow[21], Herzberg[22], McGregor[23] and others.

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[19] Pierre Samuel Du Pont (1870 – 1954) was an American entrepreneur and was president of General Motors from 1915-1920.

[20] Alfred Pritchard Sloan (1875 – 1966) was an American business executive. He was a long-time president, chairman, and CEO of General Motors.

[21] Abraham Harold Maslow (1908 – 1970) was an American psychologist who was best known for creating Maslow's hierarchy of needs, a theory of psychological health predicated on fulfilling innate human needs in priority, culminating in self-actualization.

[22] Frederick Irving Herzberg (1923 – 2000) was an American psychologist is most famous for introducing job enrichment and the Motivator-Hygiene theory.

[23] Douglas Murray McGregor (1906 – 1964) was an American management professor and is best known for his Theory X and Theory Y.

2.2.2 Recent Developments

The recent developments in POM were mainly influenced by the emerging possibilities of information technology and Japanese management practices. These period is also characterized by the different perspectives on problem solving of Western and Far East societies.

Western societies favored the reductionist method to analyze systems by breaking them down into their component parts and studying each one individually. In contrast, Far Eastern societies had a more holistic or system perspective in which the individual components are viewed much more in terms of their interactions with other subsystem in the perspective of the overall goal. A major contribution of the Western world to POM was created during World War II with the new emerged science discipline Operations Research (OR). This discipline developed several quantitative techniques such as linear programming, inventory control methods, queuing theory and simulation techniques which lead among others to the development of mathematical models for determining “optimal” lot sizes based on setup and inventory holding costs. In contrast, the Japanese, analyzed manufacturing systems in a more holistic sense and focused not on the optimization of lot sizes for given setup times. Rather, they did not see the setup times as constant and recognized the, from a system perspective, clear benefit in reducing these times. (Hopp & Spearman, 2008)

In the 1960s the primarily manufacturing competition was on cost, which resulted in a product-focused manufacturing strategy based on high-volume production and cost minimization. Reorder point systems (ROP) were used for production control followed by computerized inventory control system and material requirements planning (MRP) systems in the 1970s. At that time the Japanese just-in-time (JIT) system also boosted this efficiency trend. In the 1980s the primary competition changed to quality again under the Japanese influence of total quality management (TQM). While external quality, which is everything what the customer can see, was always of concern, the main attention was now on the internal quality of each process step and its influence to customer satisfaction. While costs and quality remained crucial, the 1990s were dominated by the time based competition. The rapid development of new products together with fast customer delivery were the new demanded abilities. (Hopp & Spearman, 2008)

A more detailed explanation of these movements, especially the associated developments in production planning and control systems, can be found in Chapter 4.4.

A good picture of the historical and recent development in POM is given by Koren (2010), who visualized the time span of the last decades over the two dimensions product variety and product volume per variant.

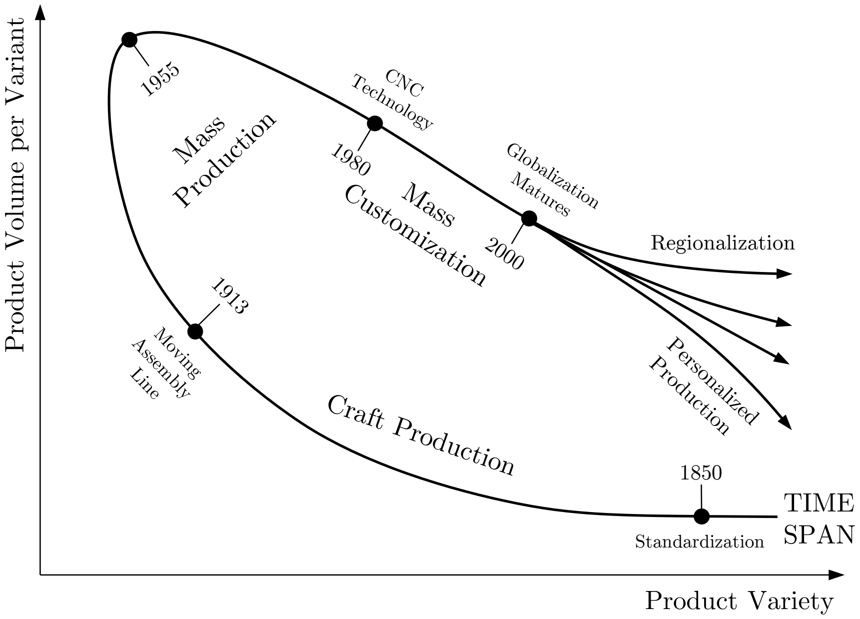

Figure 2.2: Development of production management[24]

Figure 2.2 shows the development from craft production over mass production to mass customization with the clear trend to more individualized products in the future. A recent major technological step in this development is the automation of manufacturing processes driven by electronics and information technology such as computerized numerical control (CNC), which enable the production of mass customized goods. Especially in German-speaking Europe, this time, around the 1970s, is known as the third industrial revolution (Plattform Industrie 4.0, 2013).

2.2.3 Ongoing Trends and Hypes

In the late centuries of the last millennium economists have assumed that developed economies become service societies and the classical industry segment follows a similar way as the agriculture sector did. This development could be especially seen in the economies of US, Great Britain and France, while in Germany the industrial sector remained at around 25% of the gross domestic product (GDP). Nowadays, after the financial crisis of 2007/08 several economies

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[24] adapted from the global manufacturing revolution (Koren, 2010)

changed their views and recognized that developed economies need a strong industrial sector to be successful due to the following reasons: First, the productivity contribution of the industrial sector on the economy of a country. In service industry no significant productivity increases are often possible because of the direct interaction of people. Only with productivity improvement in the industry sector, significant growth of the economy of a country is possible. The second reason is the huge innovation contribution of the industrial sector. If the production industry is outsourced to other countries also research and development activities would follow. Third is the export contribution of the industrial sector which has positive effects on the trade balance of an economy. (Bauernhansl, 2014)

Due to these reasons, several developed economies initialized programs to revitalize their industrial sector. Great Britain started the *High Value Manufacturing* (TSB, 2012) program, the USA the *Advanced Manufacturing Partnership* (PCAST, 2012) and the European Union is focusing its research and development programs in *HORIZON 2020* mainly on projects with high industrial application aspects. The German federal government even called out the fourth industrial revolution (*Industry 4.0)* with the aim to strengthen the production of Germany driven by Internet of Things and cyber physical system (Plattform Industrie 4.0, 2013). A more detailed explanation of these concepts and the associated enabling technologies can be found in Chapter 3.2.

In the USA a similar research initiative called industrial internet is aiming to bring the internet to the shop floor. Instead of the fourth revolution in manufacturing the computation of time is different in the USA. The industrial internet consortium is counting in waves in which the first wave was in general the industrial revolution followed by the internet revolution. The industrial internet is thereby seen as the third wave which will enable intelligent connected machines, advanced analytics and connected people at work (Evans & Annunziata, 2012). In logistics, the Physical Internet Initiative was founded to develop open system, interfaces and protocols that use Internet of Things technology in logistic systems (Montreuil, 2012).

However, beside the promising benefits of the concepts, these current trends can also be dangerous. The vocabulary of POM is coined by buzzwords which are often associated to a much lauded guru (Micklethwait & Wooldridge, 1996). Using these, in the past often three letter acronym (e.g. MRP, JIT, ERP), buzzwords and manufacturing firms have become flooded with waves of revolutions in recent years and Industry 4.0 is only the next one. According to Hopp & Spearman such revolutions have always *"...swept through the manufacturing community, accompanied by soaring rhetoric and passionate emotion, but with little concrete* *detail"* (2008). However, those revolutions can be dangerous for managers to become attached to trendy buzzwords and losing sight of their fundamental objectives. Beside the lack of precise definition of the underlying concept especially in practitioner literature (see Hopp & Spearman, 2003) the firm belief, nearly on a religious level, in these buzzwords has even further drawbacks. Often the underlying concepts behind trendy buzzwords offer only a single solution for all situations which is especially in situations of volatile markets where flexibility is needed by far too little (Hopp & Spearman, 2008).

2.3 Objectives and Relationships

2.3.1 Strategic and Operational Objectives

According to Hopp & Spearman (2008) the fundamental objective of operations is to *"make a good return on investment (ROI) over the long term".* The ROI is determined by three financial quantities: (a) revenue, (b) assets and (c) costs as follows:

$$ROI = \frac{revenue - costs}{assets} \tag{2.1}$$

The financial quantities can further be reduced to their operational equivalents: (a) throughput, the amount of products sold, (b) controllable assets such as inventory and (c) costs, consisting of operating expenditures of the plant. Using these equivalents Hopp & Spearman (2008) draw the following links between ROI and subordinate objectives and note several containing conflicts (see also Figure 2.3).

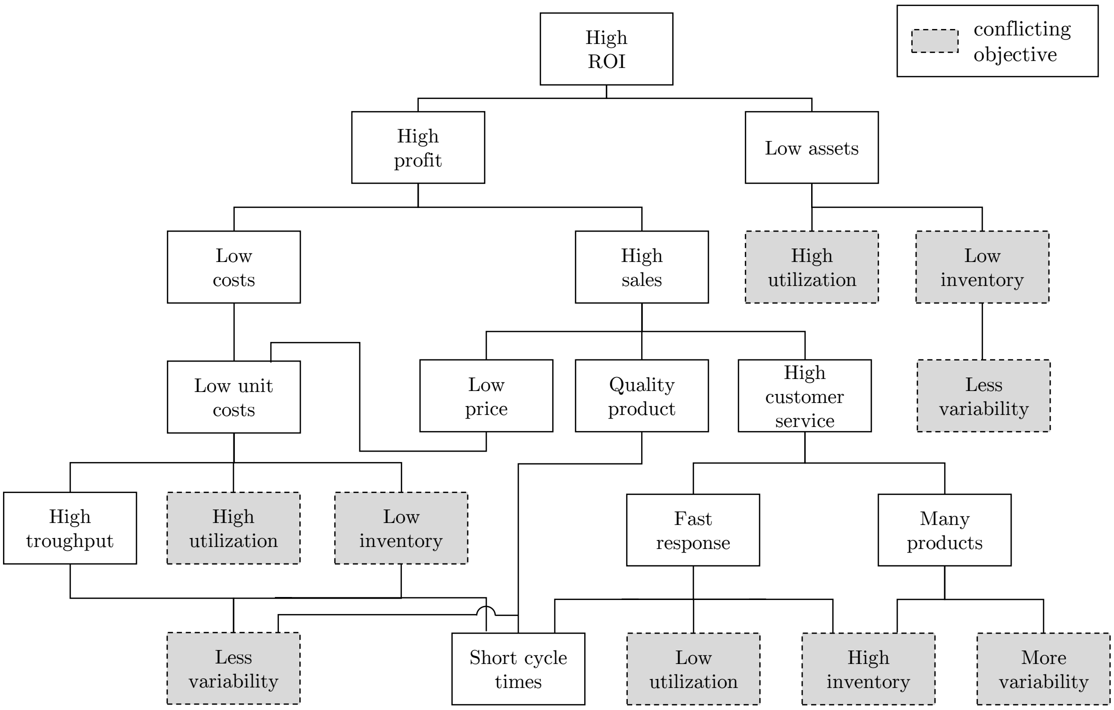

Figure 2.3: Links between fundamental and operational objectives[25]

> *High ROI can be achieved via high profit and low assets. High profit requires low costs and high sales. Low costs imply low unit*

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[25] hierarchical objectives in a manufacturing organization (Hopp & Spearman, 2008)

> *costs, which requires high throughput, high utilization and low inventory... Achieving low inventory while keeping throughput and utilization high requires variability in production to be kept low. High sales require a high-quality product that people want to buy, plus good customer service. High customer service requires fast and reliable response. Fast response requires short cycle times, low utilization and/or high inventory levels. To keep many products available requires high inventory levels and more (product) variability. However, to obtain high quality, we need less (process) variability and short cycle times (to facilitate rapid defect detection). Finally, on the assets side of the hierarchy, we need high utilization to minimize investment in capital equipment and low inventory in order to reduce money tied up in stock. As noted above, the combination of low inventory and high utilization requires low variability. (Hopp & Spearman, 2008)*

One conflict in this hierarchy is, for instance, on the one hand the need of high inventory for fast response, but on the other hand the demand of low inventory to keep total assets low. These conflicting objectives result in that the improvement of one operational target usually leads to a decline in another target dimension. This target contradiction is known in the literature by Gutenberg (1951) as the dilemma of operations planning which describes the conflict of interests between the maximization of delivery reliability and utilization and the minimization of inventory and consequentially lead time.

Nevertheless, fundamental relationships between the conflicting operational targets exist.

2.3.2 Fundamental Relationship between Objectives

In the early days of queuing theory in operations research Philp M. Morse[26] proved for the first time the relationship between arrival rate and service time in a single queuing system with certain restrictions. A queuing system consists of discrete objects that arrive at some rate to the system. Within the system these objects form one or more queues, receive service and exit. John D.C. Little[27] (1961) proved then a more general case and introduced the so called Little's law.

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[26] Philip McCord Morse (1903 – 1985) was an American physicist and pioneer of operations research. He is considered to be the father of operations research in the U.S.

[27] John Dutton Conant Little (1928) is an American Professor at the MIT and is best known for his result in operations research, the Little's law.

$$L = \lambda \times W \tag{2.2}$$

$L\ = average\ number\ of\ items\ in\ the\ queuing\ system$
$W = average\ waiting\ time\ in\ the\ system\ for\ an\ item$
$\lambda\ = average\ number\ of\ items\ arriving\ per\ unit\ time$

The Little's law says that under steady state conditions, the average number of items in a queuing system L equals the average rate at which items arrive W multiplied by the average time that an item spends in the system λ. This relationship is remarkably simple and general as it is not mentioned how many servers there are, whether each server has its own queue or a single queue for all servers, what the service time distribution are, or on what distribution of inter-arrival times, etc. (Little & Graves, 2008)

The law found several important applications, for example in the design and analysis of computer system. But it also plays a major role in the practice of POM. Hopp & Spearman (2008) refer to Little's Law as the *"...fundamental relationship between WIP, cycle time and throughput".*

$$TH = \frac{WIP}{CT} \tag{2.3}$$

It can be easily seen that (2.3) is equivalent to the Little's Law (2.2) with $TH = \lambda$, $WIP = L$ and $CT = W$. But there is a more essential difference in that the law is stated in terms of the average output rate of the system, rather than the arrival rate. This difference also reflects the perspective of a typical manufacturing operating system (Little & Graves, 2008). This law can be useful for the calculation of queue lengths, for the measurement of cycle times, for calculating inventory turns, for planning inventory and so on, and it stats that any increase in the output of a system requires either an increase in work in process or a reduction in cycle time (Hopp & Spearman, 2008).

2.3.3 Influence of Variability

The relationships that the Little's law and the derivated operating curves deliver between the averages of inventory and time is also what typical people seem to have an intuitive notion of. However, many do not have an intuition about variances and their consequences on the system (Lovejoy, 1998). OR delivers with its theory on queuing systems several insights on this issue.

The Pollacek-Kinchine formula, for example, provides a great understanding of the influences of varieties in M/G/1 queuing systems. The more general

Kingman's equation gives a good approximation for the waiting time in G/G/1[28] queueing system. By defining the utilization ρ as the proportion of the mean arrival rate r_a to the mean flow rate r_e,

$$\rho = \frac{r_a}{r_e} \tag{2.4}$$

and by measuring the variability of a queueing system by the coefficient of variation (see Chapter 2.4) with c_a of the interarrival time t_a and c_e as the coefficient of variation of the process time t_e, the waiting time t_q can be calculated with:

$$t_q = t_e \frac{\rho}{1-\rho} \frac{c_e^2 + c_a^2}{2} \tag{2.5}$$

This equation shows that the waiting time rises with the process time, average utilization and variability. Especially the utilization factor $\frac{\rho}{1-\rho}$ and the coefficients of variation $\frac{c_e^2+c_a^2}{2}$ increases the waiting time in a highly nonlinear fashion. For example a utilization of 0.5 leads to a utilization factor of 1, while a utilization of 0.8 leads to a factor of 4. Figure 2.4 graphically shows this relationship between average utilization and waiting time for different coefficients of variation.

The Operations Management-Triangle, introduced by Lovejoy (1998) is based on this relationship and states that capacity, inventory and information are substitutes in providing customer service. The OM-Triangle is obtained by fixing three extreme points on the waiting time curve, which is shown in Figure 2.4. In addition to the waiting time, the y-axis also shows the inventory (compare Little's Law). Using the OM-Triangle an operation has to decide on which end it runs its operations. Operating at the capacity point enabled quick respond to volatile demand but leads to poor average utilization. Operations with high fixed costs for capacity typically try to run at nearly 100% utilization and buffer demand variability through high inventory. Operations capable of reducing variability can run their operations at the information's point. (Lovejoy, 1998)

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[28] In queueing theory the Kendall notation is the standard system used to describe and classify a queueing node using three factors written A/S/c where A denotes the time between arrivals to the queue, S the size of jobs and c the number of servers at the node. In that notation the M stands for Markov process while the G stands for general distribution. (Kendall, 1953)

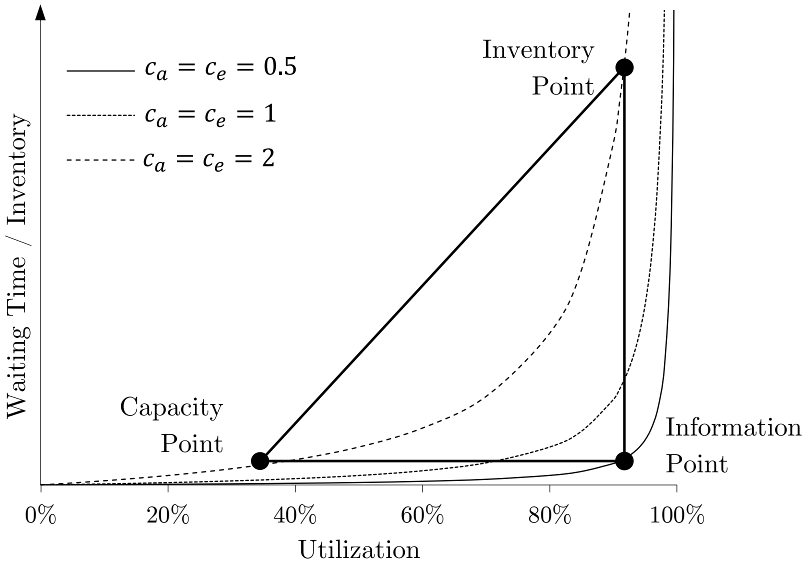

Figure 2.4: Influence of variability and the OM-triangle[29]

Beside the OM-Triangle there are also many similar frameworks. One is for example the CVI tradeoff by Klassen & Menor (2007), which describes that fundamental tradeoffs between capacity, variability and inventory. For that they also use the Kingman's equation and simplify it to the form that

$$inventory = \ capacity\ utilization\ factor \times variabilty\ factor. \tag{2.6}$$

Furthermore, Hopp & Spearman (2008) provide another concept for buffering. Variability always reduces the performance of a system which leads to a mismatch of supply and demand. To correct this misalignment additional resources are necessary. According to them three different types of buffers are available. An operation can hold either additional stock (safety inventory), additional capacities (safety capacity), or simply tell its customers delivery times which include some safety time.

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[29] based on Kingman's equation and the OM-Triangle by Lovejoy (1998)

2.4 Variability

As the previous chapter already showed that variability always degrade the performance of an operating system or how Hopp & Spearman (2008) wrote *"...the corrupting influence of variability"*, this chapter gives an overview of definitions and classifications of variability to better understand its causes.

2.4.1 Definitions

First of all the definition of the terms certainty, uncertainty, risk and variability must be clarified. Since we know from Heisenberg's principle of uncertainty[30] the world we live in is not deterministic. Also chaos theory shows that even a deterministic system can be sufficiently complex and cannot be completely predicted.

One possible definition on certainty, uncertainty and risk is coming from decision theory. In one of the most influential textbooks in decision theory by Luce & Raiffa (1957) the terms are defined as follows:

> *We shall say that we are in the realm of decision making under:*
> *(a) Certainty if each action is known to lead invariably to a specific outcome. ...*
> *(b) Risk if each action leads to one of a set of possible specific outcomes, each outcome occurring with a known probability. The probabilities are assumed to be known to the decision maker. ...*
> *(c) Uncertainty if either action or both has as its consequence a set of possible specific outcomes, but where the probabilities of these outcomes are completely unknown or are not even meaningful. (Luce & Raiffa, 1957)*

So while risk can be estimated, as it is a function of outcome and probability, it is not possible to estimate the outcome or the probability of its occurrence for uncertainty.

When it comes to decisions, intuition also plays an important role, however intuition is typically acting as if the world would be deterministic, without any randomness. In mathematics a quantitative measure of the shape of a set of points are the so called moments. While the first moment is the mean value of the points, the second describes the variance. In addition the shape is also described by the

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[30] is principle in quantum mechanics which stats that it is not possible to simultaneously arbitrarily determined precisely two complementary variables from

third (skewness), the fourth (kurtosis) and higher moments. Our intuition tends to be much less developed for second or higher moments. Therefore, random phenomena get often misinterpreted (Hopp & Spearman, 2008). In statistics the regression toward the mean[31] describes such a phenomena. Also psychology deals with problems due to randomness. For example Paul Watzlawick[32] (1987) mentions in that respect so called noncontingent reward experiment[33] in which experimental subjects in the end always format of a hypothesis of the relationship between two independent random numbers.

As already mentioned several times before, variability is in POM an often used term for the randomness in processes. A formal definition of variability is the *"quality of nonuniformity of a class of entities"* (Hopp & Spearman, 2008). A measure for variability of a random variable is the coefficient of variation c_v, which is the standard deviation σ divided by the mean μ.

$$c_v = \frac{\sigma}{\mu} \tag{2.7}$$

When talking about variability Hopp & Spearman (2008) distinguish between two main types: controllable variability, which arises directly from decisions (e.g. batch size, amount of products) and random variability, which arises from events beyond immediate control (e.g. customer demand, machine breakdown). Klassen & Menor (2007) suggest another typology shown in Table 2.1. They use the dimensions' form and source to classify the variability of a system. In the dimension form a distinction between random and predictable variability and in the dimension source a distinction between internal (i.e. process) and external (i.e. supply chain) origin is made.

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[31] Regression toward the mean is the phenomenon that if a variable is extreme on its first measurement, it will tend to be closer to the average on its second measurement - and, paradoxically, if it is extreme on its second measurement, it will tend to have been closer to the average on its first.

[32] Paul Watzlawick (1921 – 2007) was an Austrian family therapist, psychologist, communications theorist, and philosopher. His most prominent insight is that "one cannot not communicate".

[33] Subjects get presented a pairs of numbers. They have to decide whether the numbers match or not. The pairs of numbers are collected at random, and the experimenter gives his appraisal right or wrong on the basis of half rising Gaussian bell curve. The rating right is continuous with the experiment more and more frequently, leading to the formation of a hypothesis by the subject.

	Form	
Source	Random	Predictable
Internal	Quality defects Equipment breakdown Worker absenteeism	Preventative maintenance Setup time Product mix (i.e. number of SKU)
External	Arrival of individual customers Transit time for local delivery Quality of incoming supplies	Daily or seasonal cycle of demand Technical support following new product launch Supplier improvements based on learning curve

Table 2.1: Typology of the source and form of system variability[34]

2.4.2 Internal Variability

According to Klassen & Menor (2007) internal or process variability compromised all sources of variability from the internal production process. Lee (2002) characterizes a stable process by few breakdowns, stable and high yields, few quality problems, reliable suppliers, few process changes, high flexibility (easy to change over) and so on.

As an example in this respect influences of breakdowns on the internal variability is analyzed in more details. The breakdown of the bottleneck in a process impacts in the process performance in two ways: (a) the variability is increased and (b) the process capacity is reduced. Both lead to longer waiting times and increase inventory. The downtime of a machine is typically recorded by the availability A, which is the proportion of the uptime to the total available production time . (Hopp & Spearman, 2008)

$$A = \frac{MTTF}{MTTF + MTTR} \tag{2.8}$$

The mean time to failure $MTTF$ is the time a machine is running between two breakdowns and is also known as the uptime. The mean time to repair $MTTR$ is the time needed to repair the machine and is also known as the downtime.

As mentioned above a breakdown affects the variability. Hopp & Spearman (2008) quantify the impact on the variability by the squared coefficient of variation c_e^2.

$$c_e^2 = \frac{\sigma_e^2}{t_e^2} = c_0^2 + A(1-A)\frac{MTTR}{t_0} + c_r^2 A(1-A)\frac{MTTR}{t_0} \tag{2.9}$$

$\sigma_e = variance\ of\ the\ mean\ effective\ process\ time$
$t_e = effective\ process\ time$

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[34] based on Klassen & Menor (2007)

$$c_0 = variation\ of\ the\ natural\ process\ time$$
$$t_0 = natural\ process\ time$$
$$c_r = variation\ of\ repair\ time$$

The equation includes in the first term the natural variability c_0 and in the second term random outtakes. This second term is independent on the variability of the repair time, so even if the outtakes were constant this term cannot be omitted. The third term is due to the variability of the repair time.

To see the influence of the variability due to breakdowns we shall compare two different machines. The first machine has failures every 9 hours ($MTTF_1$) for 1 hour ($MTTR_1$) while the second machine has failures every 90 hours ($MTTF_2$) for 10 hour ($MTTR_2$). Obviously, by applying equation (2.8), both machines have the same availability ($A_1 = A_2$) of 90%. So one can argue that both machines equally good or bad from a capacity point of view. However, in terms of variability and consequential effects on the waiting time (inventory), these two machines are significantly different. To show the difference let's assume both machine have a natural process time of 12 minutes (0.2 hours) with a standard deviation of 6 minutes leading to a coefficient of variation of the natural process c_0 of 0.5.

$$c_0 = \frac{6}{12} = 0.5 \tag{2.10}$$

Using the equation (2.9) for both machines shows that the first machine with shorter but more frequent breakdowns has a much lower squared coefficient of variation of the mean effective process time than the second machine.

$$c_{e1}^2 = 0.5^2 + 0.9 \times (1 - 0.9) \times \frac{1}{0.2} + 1^2 \times 0.9 \times (1 - 0.9) \times \frac{1}{0.2} = 1.15 \tag{2.11}$$

$$c_{e2}^2 = 0.5^2 + 0.9 \times (1 - 0.9) \times \frac{5}{0.2} + 1^2 \times 0.9 \times (1 - 0.9) \times \frac{5}{0.2} = 9.25 \tag{2.12}$$

By using the Kingman's equation it can be shown that the average waiting time at the second machine is over four times higher than at the first machine.

Generally, machine breakdowns are only one reason for the internal variability. A common second reason are quality problems which can be viewed similar to breakdowns in their behavior. A process with a stable yield rate is in that respect preferable to a process in which full lots can be scraped from time to time.

A widely used measure to measure the performance of a process in terms of downtime and quality losses is the overall equipment effectiveness (OEE), which was introduced within the concept of total productiveness maintenance (TPM). The OEE combines the availability A, the speed S and the quality rate Q into one performance measure. (Nakajima, 1988)

$$OEE = A \times S \times Q \tag{2.13}$$

The speed measure captures to which extent the maximum production rate is used. For example, a machine's maximum operation's rate would be 100 pieces per time unit, however the machine is running at a rate of 90 pieces per unit which leads to a speed performance rate of 90%. The quality rate is a measure for the yield, which is the probability that a particular part is defect. For instance 90% yield (or quality rate) means that in average 10% of the pieces have to be scraped or reworked. The availability is already defined above. For example if all three variables have a value of 90% the OEE has a value 72.9%. However, the OEE only captures the capacity effects of downtimes, quality and speed losses. Their above mentioned impact on the variability and the thereby on the average flow time is not included.

2.4.3 External Variability

The external or supply chain variability is the second big source of variability. One important cause of the external variability is the product portfolio. Obviously, the more products an operation offers, the greater the variability. According to Hopp & Spearman (2008) this type of variability can be viewed as good variability if the customers expect a huge product portfolio. Remember the success that GM had with the multi-product strategy over Ford's Model T (Chapter 2.2.1). However, this type of variability can lead to high complexity when it comes to forecasting and production planning. Another phenomenon which is also a driver of the external variability is the bullwhip effect. This phenomenon was first recognized by Forrester (1961) and refers to the demand variability increases upstream in the supply chain. The main reasons for that are according to Lee et al. (1997) the following:

- Demand signal processing: small changes in the customer demand in comparison to the forecast are interpreted as increase or decrease in the future demand leading to adjustments of the order quantity
- Order batching: the customer demand batched by replenishment policies and not passed directly to the supplier
- Prize variations: discounts and changing prices increase the bullwhip effect
- The rationing game: if a manufacturer is rationing the production output among customers, the customers start to order more.

2.5 Flexibility and associated Properties

Flexibility and associated properties such as adaptability and agility are characteristics of a manufacturing systems to handle uncertainties and variabilities from internal and external sources. In a deterministic and stationary environment an operation would need no flexibility, with growing uncertainty and variability a manufacturing operation must be flexible enough to ensure the business on the long run.

2.5.1 Flexibility

In literature, a very large variety of definitions for the term manufacturing flexibility exist. The reviews of Sethi & Sethi (1990), Toni & Toncha (1998) and Koste & Malhotra (1999) give a very good overview on this topic.

Zelenovich (1982) defines manufacturing flexibility as the ability to adapt to changes in environmental condition and in the process requirements which implies the exogenous and the endogenous nature of flexibility. Slack (1987) considered flexibility as the general ability to adapt/change and concerns the range of states reachable and time for moving. Thereby he distinguishes between range, how much the system can change, and response, how fast the system can change, flexibility. This hypothesis is taken up by Upton (1995) who defines flexibility as *"...the ability to change or react with little penalty in time, effort, cost or performance".* Concluding these definitions, flexibility has a time and a range component and furthermore the changes can arise externally and internally. Which goes in line with the definition of APICS.

> *The ability of the manufacturing system to respond quickly, in terms of range and time, to external or internal changes. (APICS, 2013)*

In production science literature, several publications dealing with the developments of flexible manufacturing system (FMS) (compare Browne et al. (1984)) were issued in the 80th and 90th of the last century (Toni & Tonchia, 1998). Thereby also the costs for the provision of flexibility potentials were analyzed. While the lack of reactivity can lead to opportunity costs also several measures taken to increase flexibility are not for free.

Dimensions and Structures

Similar to the variety of definitions are the different dimensions which exist for flexibility in manufacturing. Furthermore, several classifications try to structure these various manufacturing flexibility dimensions.

Sethi & Sethi (1990) build a hierarchical linkage between the various types for flexibility. This hierarchical classification indicates that the lowest level (component or basic flexibility) forms the basis for the system and aggregated flexibility dimensions. Thereby, the production flexibility is the result of the configuration of different lower level system flexibilities.

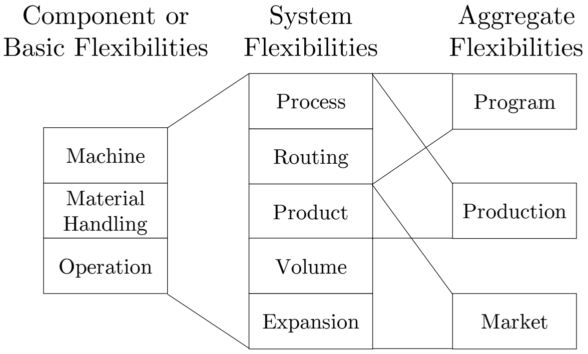

Figure 2.5: Linkages between the various flexibilities[35]

Another hierarchical structure of the different flexibility dimensions originates from Koste & Malhotra (1999) and is based on a corporate organization structure with the five levels: strategic business unit, functional, plant, shop floor and individual resource (see Figure 2.6).

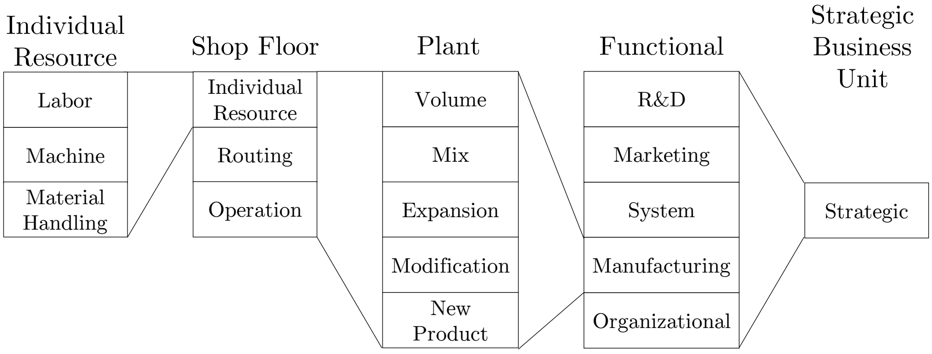

Figure 2.6: Hierarchy of flexibility dimensions[36]

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[35] based on Sethi & Sethi (1990)

[36] based on Koste & Malhotra (1999)

2.5.2 Agility and Adaptability

Closely related to the general property flexibility are the properties agility, adaptability and responsiveness.

Agility

The literature on agility started to accumulate in the 1990s proposing agile manufacturing as a new manufacturing paradigm. Again several definitions exist. According to Goldmann et al. (1995) agility is "*a comprehensive response to the business challenges of profiting from rapidly changing, continual fragmenting, global market for high quality and performance customer configured goods and services.*" The main distinction between flexibility and agility is the character of the situations requiring change. While flexible changes are responses to known situations agility is responding to unpredictable changes in the market or in the customer demand. Furthermore, the scope of agility in comparison to flexibility is more on the business level than on the operation level (Bernardes & Hanna, 2009).

Adaptability

The German POM literature is currently strongly coining by the term "Wandlungsfähigkeit" which stands for adaptability. While flexibility refers to the ability of a production system to adapt quickly and with very little cost to changing factors so that within a certain corridor a pre-determined amount of change can be caught. The adaptability is seen as a potential to perform organizational and technological changes reactive or proactive even beyond the corridors. (Nyhuis, et al., 2008)

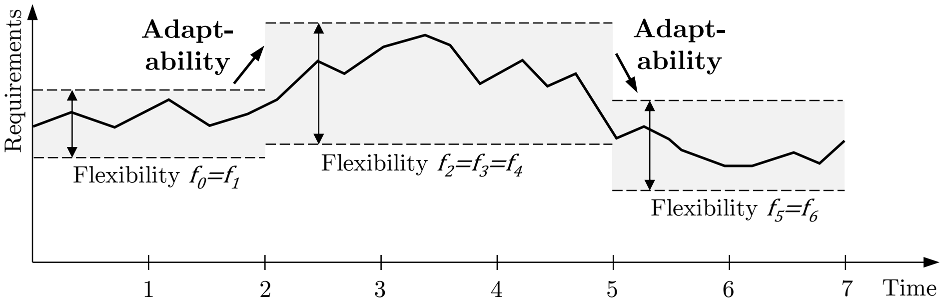

Figure 2.7: Distinction between flexibility and adaptability[37]

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[37] based on Nyhuis et al. (2008)

Figure 2.7 shows the difference between flexibility and adaptability. During time period 0 and 1 the system has a certain flexibility $f_0 = f_1$. As the requirements of period 2 are beyond the flexibility of period 0 and 1 a change in the flexibility corridor to $f_2 = f_3 = f_4$ is needed. For that an adaptable manufacturing system has no explicit limits on its implementation and a scope for possible changes is considered. For the adaption cost and time for additional investments are needed. (Nyhuis, et al., 2008)

Relationship between Agility, Adaptability and Flexibility

Sousa et al. (1999) present the relationships of agility, adaptability and flexibility properties in the manufacturing system shown in Figure 2.8.

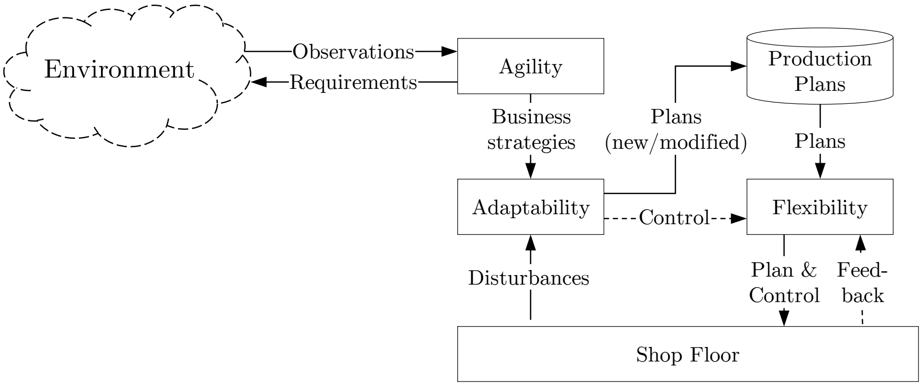

Figure 2.8: Relationships between agility, adaptability and flexibility[38]

According to them flexibility is the simplest approach and relates directly to the shop floor allowing to "*...react accordingly in a predefined set of possibilities to meet primary disturbances in production".* Furthermore, adaptability "*...allows run-time specifications and changes according to momentary requirements".* Moreover, agility is related to the strategic options and has to "*continuously evolve, adapting internally and pursuing external strategic partnerships that complement its own competencies*". (Sousa, et al., 1999)

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[38] based on Sousa et al. (1999)

3

CHAPTER

Informatization in Production

Information is not knowledge.
Albert Einstein (1879 – 1955)

Informatization always played a major role in manufacturing. Early after the invention of the computer concepts based on information technology shaped the whole manufacturing industry. Nowadays, with the new possibilities of interconnectivity a further wave of innovation is expected to change the way of production and also production planning.

This chapter gives an overview on the general definitions as well as the basic concepts such as computer integrated manufacturing and digital factory. Moreover, new emerging technologies such as Internet of Things, cyber physical system and their application in the manufacturing paradigm Industry 4.0 are explained in this chapter. Also the impacts of the informatization on production planning and control are shown. Thereby, especially the trends of the increase of the quantity and quality of data are investigated.

3.1 Definitions

The term informatization contains information, which is defined in the next chapter. Furthermore, a historical reflection of the informatization from simple data processing to the information age is given.

3.1.1 Data, Information, Knowledge, Understanding, Wisdom

The system theorist Russell Ackoff (1989) gives precise definitions on information related terms which he classifies into five categories: data, information, knowledge, understanding and wisdom. According to him data *"...is raw. It simply exists and has no significance beyond its existence (in and of itself). It can exist in any form, usable or not. It does not have meaning of itself. In computer parlance, a spreadsheet generally starts out by holding data."*

Next, information *"...is data that has been given meaning by way of relational connection. This meaning can be useful, but does not have to be. In computer parlance, a relational database makes information from the data stored within it."*

Furthermore, knowledge *"...is the appropriate collection of information, such that its intent is to be useful. Knowledge is a deterministic process. When someone memorizes information (as less aspiring test-bound students often do), then they have amassed knowledge. This knowledge has useful meaning to them, but it does not provide for, in and of itself, an integration such as would infer further knowledge."*

Moreover, understanding *"...is an interpolative and probabilistic process. It is cognitive and analytical. It is the process by which I can take knowledge and synthesize new knowledge from the previously held knowledge. The difference between understanding and knowledge is the difference between learning and memorizing. People who have understanding can undertake useful actions because they can synthesize new knowledge, or in some cases, at least new information, from what is previously known (and understood). That is, understanding can build upon currently held information, knowledge and understanding itself. In computer parlance, AI systems possess understanding in the sense that they are able to synthesize new knowledge from previously stored information and knowledge."*

And finally Ackoff (1989) gives the following definition on wisdom, which "*...is an extrapolative and non-deterministic, non-probabilistic process. It calls upon all* *the previous levels of consciousness, and specifically upon special types of human programming (moral, ethical codes, etc.). It beckons to give us understanding about which there has previously been no understanding, and in doing so, goes far beyond understanding itself. It is the essence of philosophical probing. Unlike the previous four levels, it asks questions to which there is no (easily-achievable) answer, and in some cases, to which there can be no humanly-known answer period. Wisdom is therefore, the process by which we also discern, or judge, between right and wrong, good and bad. I personally believe that computers do not have, and will never have the ability to possess wisdom. Wisdom is a uniquely human state, or as I see it, wisdom requires one to have a soul, for it resides as much in the heart as in the mind. And a soul is something machines will never possess (or perhaps I should reword that to say, a soul is something that, in general, will never possess a machine)."*

Ackoff (1989) indicates also that the first four categories are related to the past, they deal with *"...what has been or what is known".* Only the fifth category, wisdom deals with *"...the future because it incorporates vision and design. With wisdom people can create the future rather than just grasp the present and past."*

Bellinger et al. (2004) condense the definitions of Ackoff in the following way. While data are pure symbols, information provides answers to "who", "what", "where", and "when" questions. Knowledge is the application of data and information and gives answers on "how" questions. Understanding is the appreciation of "why" and wisdom is the evaluated understanding. Furthermore, Bellinger et al. (2004) provide a diagram in which the transition from data, to information, to knowledge and finally to wisdom is described. In this relationship understanding is not a separate level, it is instead the support of the transition from each stage to the next (see Figure 3.1).

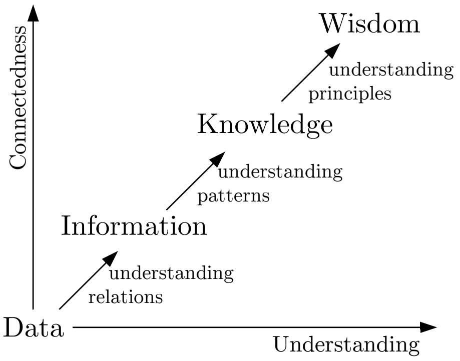

Figure 3.1: Relationships between data, information, knowledge and wisdom[39]

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[39] based on (Bellinger, et al., 2004)

3.1.2 Informatization

The year of birth of computer lies somewhere in the 1930th or 1940th depending on the time reckoning. In 1936 Alan Turing[40] published the groundbreaking paper *On Computable Numbers* (Turing, 1936) in which he suggested a definition on the term computable. Only numbers that can be calculated with a Turing machine are considered to be computable. A Turing machine consists of a storage and a processor, which can perform only simple conversions of zeros and ones. In 1938 Konrad Zuse[41] finished his work on Z1, a mechanical device, which could perform the four basic arithmetical operations. Later on, in 1941 he built the Z3 with the similar logic as the Z1 but based on relay technique. Often in the US the in 1945 finished ENIAC (Electronic Numerical Integrator and Computer) is considered as the first electronic general-purpose computer. The ENIAC was Turing-complete, digital, and initially designed to calculate artillery firing tables for the United States Army's Ballistic Research Laboratory (Rojas, 1996).

While in these early days computers were simple data processing machines, later on the idea of processing data to produce information by computers arose. The terms information technology (IT) and information and communication technology (ICT) now describe the computer field. While IT is associated with hardware and software technologies, ICT stresses more the role of communications (Davenport, 1997). Marc Porat (1977) categories the ages of human civilization since the middle age into the agricultural age, the industrial age and the information age. What industrialization was for the industrial age, nowadays informatization is for the information age. This process of becoming information dependent is also known as computerization. According to Castells (1996) there is even the further trend towards a network society driven by this informatization.

The term informatization has mostly been used within the context of national development. However, this trend is currently also taking place in the classical industrial production and the associated support processes. The next chapter gives an overview on the IT concepts used in production.

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[40] Alan Mathison Turing (1912 – 1954) was a British pioneering computer scientist, mathematician, logician, cryptanalyst, and philosopher. He was highly influential in the development of computer science, providing a formalization of the concepts of algorithm and computation with the Turing machine, which can be considered a model of a general purpose computer. Turing is widely considered to be the father of theoretical computer science and artificial intelligence.

[41] Konrad Zuse (1910 – 1995) was a German civil engineer, inventor and computer pioneer. His greatest achievement was the world's first functional, program-controlled, Turing-complete computer.

3.2 IT in Production

The need to reduce the time to market with growing demand for more customized products have let to the excessive use of IT in production. Their application ranges from simple machining applications to complex PPC optimization applications. The increasing power and decreasing costs of IT solutions have spurred these implementations. An early example of the introduction of IT into the manufacturing world was the concept of computer integrated manufacturing. This concept favored the enhancement of performance, efficiency, operational flexibility, product quality, response behavior to market, differentiations, and time to market. However, the full advantages of IT were poorly understood at that time and the benefits of computer integrated manufacturing could not be fully exploited. Later on, the advances in microprocessor technology, the internet era, standardized software interfaces, the use of mature techniques for software design and development paved the way for the excessive use of IT in manufacturing. New concepts such as the digital factory/manufacturing emerged and there is even the vision of total interconnected and collaborating factory networks using internet of things and cyber-physical systems.

3.2.1 Computer Integrated Manufacturing

The initial concept was first recognized by Harrington (1973) who introduced the name computer integrated manufacturing (CIM) in his book of that title. After some years, people began to realize the potential benefits of this concept and several publications on CIM followed.

Definitions

Several definitions of CIM emphasizing various aspects of it as a philosophy, an organizational structure or the integration of several computer systems exist. The APICS define CIM as the following:

> *The integration of the total manufacturing organization through the use of computer systems and managerial philosophies that improve the organization's effectiveness; the application of a computer to bridge various computerized systems and connect them into a coherent, integrated whole. For example, budgets, CAD/CAM, process controls, group technology systems, MRP II, and financial reporting systems are linked and interfaced. (APICS, 2013)*

Thereby the term integration plays a crucial role in the CIM philosophy and stands for two meanings. First, the principle of integrated data processing. Especially Taylor (see Chapter 0) shaped the organizations with his functional separation of work. To speed up these individual sub functions, the effort for information forwarding throughout the overall process should be significantly reduced through the use of a common data base. Second, also the functions within an overall process should be closer integrated. Through the support of database systems and user friendly transaction processing systems, the capabilities of people to perform complex work packages increases and sub-functions can be brought together (Scheer, 1989).

Close related with CIM are also several computer-aided systems (CAx) which include computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), computer-aided quality assurance (CAQ) and computer-aided process planning (CAP/CAPP). The APICS (2013) defines CAD as *"the use of computers in interactive engineering drawing and storage of designs. Programs complete the layout, geometric transformations, projections, rotations, magnifications, and interval (cross-section) views of a part and its relationship with other parts".* CAM is defined by APICS (2013) as *"the use of computers to program, direct, and control production equipment in the fabrication of manufactured items".* CAPP is defined by APICS (2013) as *"a method of process planning in which a computer system assists in the development of manufacturing process plans (defining operation sequences, machine and tooling requirements, cut parameters, part tolerances, inspection criteria, and other items). Artificial intelligence and classification and coding systems may be used in the generation of the process plan".* Furthermore, CAE is defined by the APICS (2013) as *"the process of generating and testing engineering specifications on a computer workstation".*

Concept

For CIM several concepts exist of which the two most prominent ones are the CIM Wheel of the Society of Manufacturing Engineers (SME) and the CIM Y-Model by Scheer (1989) (Salvendy, 2001).

The CIM Wheel provides a view on the relationships in a three-layer structured enterprise as shown in Figure 3.2.

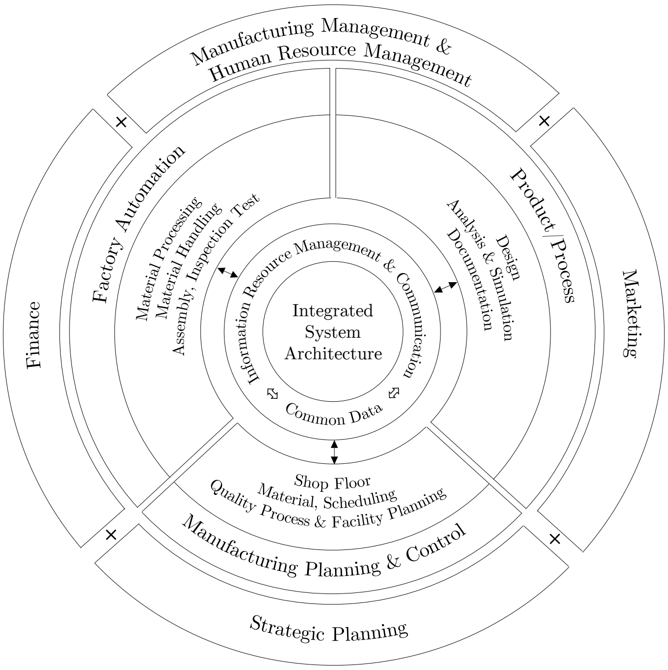

Figure 3.2: Computer integrated manufacturing wheel[42]

The inner core represents the common database and also includes information resource management and communication systems. Surrounded and connected to this center is the middle layer with three process segments: product and process, factory automation and also the PPC. These process segments include all activities from the design to the manufacturing phase of the product life cycle. Furthermore, the outer layer represents the general management and human resource management (Salvendy, 2001).

Another CIM concept originates from Scheer (1989) and is called Y-Model (see Figure 3.3) Through CIM all operational information systems of an industrial company should be linked. In particular, a link between business and technical systems should be established. The Y-model shows the components involved in the integration of both areas and attempts to connect the technical (CAD, CAM, CAP, CAQ) and the business dispositive functional areas in the PPC.

Despite these great and accepted concepts of CIM Scheer is already warning in the late 80th that CIM could become just another buzzword because the realization possibilities have not become fully mature. Not only suitable IT-tools for the realization of CIM are missing, also the organizational know-how to integrate all functions into holistic process is often not available (Scheer, 1989).

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[42] based on the SME CIM wheel (Salvendy, 2001)

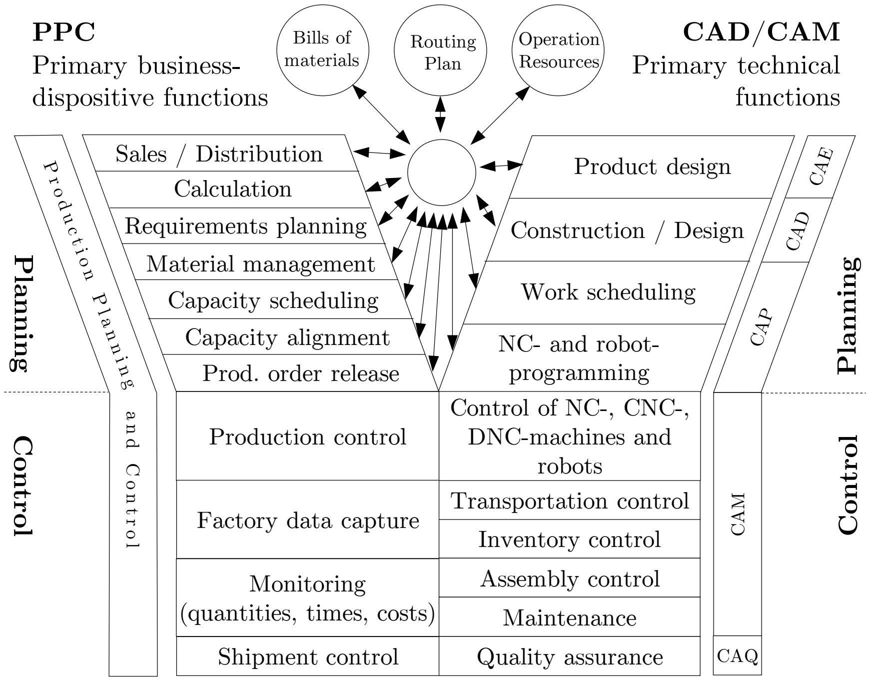

Figure 3.3: Computer integrated manufacturing Y-model[43]

3.2.2 Digital Factory

The concept of the digital factory focuses on the integration of methods and tools for planning and testing the product and the related production control of the factory. According to VDI 4499 (2011) the following processes are integrated:

- Product development, testing and optimization
- Production process development and optimization
- Plant design and improvement
- Operative PPC

Therefore, the digital factory concept includes on the one hand the whole product and production engineering processes and on the other hand also the operative PPC tasks (see Figure 3.4).

On the product engineering side product data management (PDM) and product life-cycle management (PLM) systems allow to perform various data management tasks such as workflow management and change management. PDM systems can integrate and manage all applications, information and processes that define a product. PLM systems are integrated information driven systems that support all aspects of a product life cycle from the design, through manufacturing and afterwards service to finally its disposal. Both systems can significantly reduce the time to market, generate saving through the reuse of original data and

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[43] based on Y-model by Scheer (1989)

completely integrate whole engineering workflows (Chryssolouris, et al., 2009). The common access to a single data base of all product related data furthermore enables the real time virtual collaboration of globally located teams (Kühn, 2006).

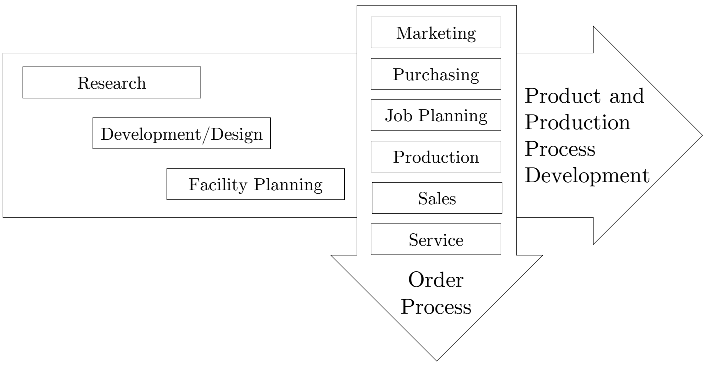

Figure 3.4: Digital factory processes[44]

But the concept of the digital factory goes far beyond product engineering. Also the production engineering such as the design of the plant layout, material flows, line balancing or offline robotics programming are included (Kühn, 2006). For that computer simulation has become one of the most used techniques to design and investigate complex manufacturing systems. Computer simulation offers a great advantage in the studying and analyzing of the stochastically system behavior of manufacturing systems. The time and costs for decision making can thereby be reduced significantly. Digital mock-up (DMU) software packages allow to visualize the production process, while discrete event simulation (DES) software helps in the finding of optimal production system settings such as the location and size of inventory buffers. (Chryssolouris, et al., 2009)

A further recent development is the integration of real-time data from the shop floor into the digital models. Through the use of wireless technologies on the shop floor, such as radiofrequency identification (RFID), the accurate and timely identification of objects, which are moving through the supply chain, is possible (Chryssolouris, et al., 2009). The basic idea of the interaction of various things tagged with RFID sensors with their environment is then called Internet of Things (IoT).

3.2.3 Internet of Things

The Internet of Things (IoT) is the interconnection of uniquely identifiable devices within the existing Internet infrastructure. According to Atzori et al.

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[44] based on VDI 4499 (2011)

(2010) the basic idea of this novel paradigm is *"...the pervasive presence around us of a variety of things or objects – such as RFID tags, sensors, actuators, mobile phones, etc. which through unique addressing schemes, are able to interact with each other and cooperate with their neighbors to reach a common goal."*

Unquestionable this visionary concept would have a high impact on several aspects of everyday life and even more apparent consequences in automation, manufacturing and logistics. The US National Intelligence Council includes IoT in the list of the six *disruptive civil technologies* with potential impact on US national power. However, as the first definitions of IoT had a mainly things oriented perspective, RFID is only an enabling forefront technology driving this vision. Near field communication (NFC) and wireless sensor and actuator networks (WSAN) are together recognizes with RFID technology as *"...the atomic components that will link the real world with the digital world"* (Atzori, et al., 2010). Together with a middleware software layer several services can be provided for various applications. In the logistic and production application domain the real time monitoring of almost every-*thing* in the supply chain can be enabled by IoT. This advanced connectivity of objects, devices, systems and services goes far beyond the classical machine-to-machine (M2M) communications. Smart industrial management systems would enable an automated control and a real-time optimization of the production system by using the data provided by a large number of networked sensors and actuators. These, through networks interacting elements with physical input and output, are also called cyber physical systems (Atzori, et al., 2010).

However, IoT also has some open issues and a huge research effort is still needed to make the IoT concept feasible. One issue is the standardization of RFID and associated technologies. Another open issue is the addressing of the objects captures in IoT. Furthermore, there are also serious threats, mainly in respect to security. IoT is extremely vulnerable to attacks due to the wireless communication and the most of the time unattached physically easy to attack tags. Because of the low computation and energy capabilities of IoT components, complex security schemes are not possible. Finally, also privacy issues have to be clarified, because through the possibilities of massive data collecting and mining, it would be impossible for a human individual to personally control the disclosure of their individual information (Atzori, et al., 2010).

3.2.4 Cyber Physical Systems

According to Lee (2010) there are three main ongoing trends in computing. First, the data and device proliferation will increase dramatically driven by *Moore's* *law*[45]. Sensor networks and portable smart devices are only two examples for that. The slogan *embedded, everywhere* from the US National Research Council (2001) will become true. The second trend is the integration at scale. Because of the fact that isolation has its costs, the integration from ubiquitous embedded devices to complex system with global integration will grow in future. The third trend is due to the biological evolution. The exponential proliferation of embedded devices is not matched by a corresponding increase in human ability to consume information. Therefore, there is an ongoing trend of increasing autonomy or *humans out of the loop* towards distributed cyber physical information distillation and control system of embedded devices.

Cyber physical systems (CPS) are defined by Lee (2008) as the following:

> *Cyber physical systems are integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa. (Lee, 2008)*

The key enabler for CPS is the ability to interact with the physical world and other embedded controllers through communication. According to Rajkumar et al. (2010) this integration of computing and communication technologies into physical systems will transform the physical world around us as the internet transformed how humans interact with one another. CPS are pushed by several ongoing technological developments such as low cost and increased capacity sensors, low-power and high capacity computing devices, wireless communication technologies and also extensive internet bandwidth. However, the continuous control of dynamic not entirely predictable physical and engineered system has still some open issues. Mainly the real-time performance[46] of the computerized control is still an open challenge.

The use of CPS in production systems is also called cyber physical production system (CPPS). Through such CPPS a quick respond to changing market and supply chain conditions should be possible. Moreover, real-time information acquisition of the position and condition of production goods in global supply chains gets possible. A closer view on the impacts of CPS have especially to PPC is given in Chapter 3.3.

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[45] *Moore's law* is the observation that, over the history of computing hardware, the number of transistors in a dense integrated circuit doubles approximately every two years. (Moore, 1998)

[46] A real-time system is one which "...controls an environment by receiving data, processing them, and returning the results sufficiently quickly to affect the environment at that time." (Martin, 1965)

3.2.5 Industry 4.0

Industry 4.0, the fourth industrial revolution, is a research policy of the German federal government with the aim to strengthen the German industrial sector (see detailed aims in Chapter 2.2.3). Within literature various aspects on Industry 4.0 are highlighted and therefore also widely different interpretations exist. However, the enabling technologies IoT and CPS are nearly mentioned everywhere. In the white paper of the recommendations for implementing Industry 4.0 the central statement is that both technologies are coming to the manufacturing environment to change, or even revolutionize, the way how goods are produced.

> *In essence, Industry 4.0 will involve the technical integrations of cyber physical systems into manufacturing and logistics and the use of the Internet of Things and Services in industrial processes. This will have implications for value creation, business models, downstream service and work organization (Plattform Industrie 4.0, 2013).*

Huge potentials are expected through this next "revolution" in manufacturing. Some of them are the following (Plattform Industrie 4.0, 2013):

- Meeting individual customer requirements: individual, customer-specific criteria in the design, configuration, ordering, planning, manufacture and operation phases and last-minute changes are possible
- Flexibility: dynamic configuration through the use of CPS is possible
- Optimized decision-taking: through the end-to-end real-time transparency of all data available
- Resource productivity and efficiency: through the continuous optimized manufacturing processes by CPS

However, some scientists also are of a more critical view regarding the visions of Industry 4.0. Like CIM, the technology-centered perspective of Industry 4.0 is ignoring social and organizational aspects in manufacturing. According to Brödner (2014) a debacle such as with CIM will follow if these deficits are not solved. There is clear risk of putting all our responsibilities into the hands of machines. As the automation gets more complex through interdependencies among algorithms, databases and sensors the potential of failures multiplies. A small error can cause through system dynamical effects major incidents. According to Bainbridge (1983) there is even an irony of automation, which means that the more advanced a control system is, the more crucial may be the contribution of the human operator, due to the fact that even a highly automated system needs human beings for supervision, adjustment, maintenance and improvements.

In that respect also the different perspectives of artificial intelligence (AI) (Minsky, 1988) and intelligence amplification (IA) (Norman, 1993) have to be mentioned. While AI stands for smart machines and autonomous agents, IA emphasis machines (things) that make us smart. This second perspective involves humans much more in their decision-making and responsibility.

Nevertheless, of these questionable aspects of getting the humans out of the loop, the further informatization in production will have major influences on the operative PPC processes which get analyzed in the next chapter.

3.3 IT in Production Planning and Control

In Industry 4.0 the operative PPC is often seen in a real-time machine learning optimization loop using realistic in-detail models of the production system and the sensors and actuators of the CPPS. Thereby the vision of continuous improvements through self-optimization of the controls exist. The real time data and the tracking of all activities and objects in the real world can be used in PPC. This new level availability of data will have major impacts on the overall transparency in the inventory and the shop floor status but will also drive complexity through the enormous amount of data that can be collected. As one major trend this quantitative increase of data will lead to decentralized decision making with the use of agent based computation in manufacturing. Furthermore, also data quality will experience tremendous improvements through new the technological possibilities.

3.3.1 Complexity and Decentralized Decision Making

Complex systems, complex relationships and complex problems are coining our everyday life. Most people also seem to have an intuitive comprehension of complexity, which somehow has something to do with difficult, incomprehensible, inscrutable, inexplicable and so on. The research area cybernetics gives in that respect some more precise answers.

Cybernetics is coming from the Greek term *kybernetike*, meaning “governance”. The founder of this research area was Norbert Wiener who describes the term cybernetics in the title of his book *Cybernetics: or Control and Communication in the Animal and the Machine* (Wiener, 1948). The basic finding of cybernetics is that a system consists in addition to the energy and matter primarily through the essential basic elements of ordering and organizing information. Cybernetics distinguishes between simple and complex systems in which simple systems are no big problems, concerning their regulation and control. Serious problems in the control only occur if a system is complex. Thereby strictly speaking it is not the system that must be controlled it is the complexity of the system. The core question of cybernetics therefore is: *How to get the complexity of a system under control?* (Malik, 2002)

The complexity of a system is measureable by using the variety. This term was introduced by W. Ross Ashby to denote the count of the total number of states of a system.

> *Thus, if the order of occurrence is ignored, the collection*

> *c, b, c, a, c, c, a, b, c, b, b, a*
> *which contains twelve elements, contains only three distinct elements a, b, c. Such a set will be said to have a variety of three elements. (Ashby, 1956)*

While a simple system has only a few possible states a complex system has a much higher wealth of variants and is therefore much more pretentious to keep under control. Ashy presented also views on controllers and controlled system which are nowadays generally used. Among these is also the law of requisite variety which is today highly prized amount experts of the field of cybernetics. The law states that a system which controls another is able to compensate more disturbances in the control process, the greater its variety is.

> *Only variety can destroy variety. (Ashby, 1956)*

This means, in other words, that the only way you can control your destiny is to be more flexible than your environment. Therefore, any organization must have as much variety and flexibility as the world around it which is an important insight. The often used slogan *keep it simple* has therefore only narrow authorization. If the environment is complex then the company must be able to develop sufficient complexity to respond properly (Malik, 2002).

A way to deal with this requested complexity by the law of requisite variety is decentralized decision making. This basic idea of decentralization and autonomy is also grounded in the visions of Industry 4.0 with its CPS (Bauernhansl, 2014). Agent-based computation is here the paradigm which provides the supporting technology that can handle the new degree of availability of information and has the ability to process it quickly (Monostori, et al., 2006).

Agent-based Computation

The traditional approach in PPC based on centralized or hierarchical control structures, presents good characteristic in terms of productivity, especially due to its optimization capabilities. However, the dynamic and adaptive responses to change due to increasing volatility of the market and disturbances in manufacturing disfavor the rigid, top-town hierarchical planning architectures. Instead systems are needed which can response in real-time to abrupt changes. Decentered organized, collaborating multi-agent-system fulfill this demanded property. The theory of these agent-based systems goes back to the early 90s with the research in distributed artificial intelligence (DAI) (Monostori, et al., 2006).

According to Wooldridge & Jennings (1995) an agent is a software process with the following properties:

> *Autonomy: agents operate without the direct intervention of humans or others, and have control over their actions and internal state...*
> *Social ability: agents interact with other agents (possibly humans) via some kind of agent-communication language...*
> *Reactivity: agents perceive their environment..., and respond in a timely fashion to changes that occur in it.*
> *Pro-activeness: agents do not simply act in response to their environment, they are able to exhibit goal-directed behaviors by taking the initiative. (Wooldridge & Jennings, 1995)*

Furthermore, multi-agent systems are defined as a collection of agents that are capable of interacting in order to achieve their individual goals. With these properties the response requirements in PPC should be fulfilled (Leitao, 2009). The change from the conventional, centralized approach to the distributed, cooperative approach is shown in Figure 3.5.

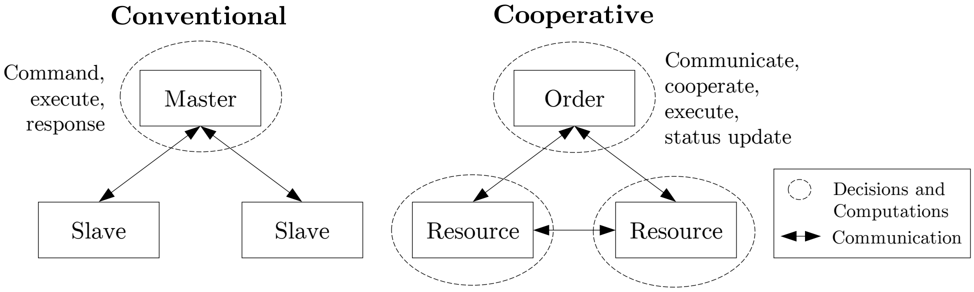

Figure 3.5: Conventional and cooperative approach to decision-making[47]

Application in PPC

In the beginnings of the nineties with the international collaborative research program called *Intelligent Manufacturing Systems* (IMS) several paradigms for the factory of the future based on agent-based computing were developed. Bionic manufacturing (Okino, 1993) is based on ideas from the nature such as enzymes which act as coordinates and hormones which represent policies and strategies. The fractal manufacturing (Warnecke, 1993) concept is descended from mathematics and the theory of chaos. A fractal unit is the smallest component in this concept which has the features of self-organization, self-similarity and self-optimization. Holonic manufacturing (Van Brussel, et al., 1998) is based on

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[47] adopted from Marik & McFarlane (2005)

the concepts of Arthur Koestler who tried to define a hybrid nature of the structure of living organisms and social groups. Holons are self-containing wholes to their subordinated parts and can be at the same time a subunit from a larger system (other holon). Holons have two essential attributes which are autonomous and cooperative. Good overviews and comparisons on these paradigms can be found in Tharumarajah, et al. (1998) and Christo & Cardeira (2007). Nevertheless, all these paradigms suggest that the manufacturing system still need a hierarchical structure beside the increasing autonomy of the individual entities in order to resolve inter-entity conflicts and to guarantee the overall goal-orientation and coherence (Sousa, et al., 1999).

In the visions of Industry 4.0 the CPS and IoT are now seen as the enabling technology of these agent-based manufacturing paradigms (Bauernhansl, 2014; Bildstein & Seidelmann, 2014; Hompel & Henke, 2014). Especially the task of real time manufacturing scheduling involves low-level task assignment and execution decision with considerable time constraints. Agent-based computation is expected to provide more reactive and robust solutions in the real-time control of production processes in comparison to the centralized, rigid top-down structures of classical PPC (Marik & McFarlane, 2005). Another benefit is the re-configurability of agent-based solutions, which support the adaptable plug-and-operate approach. The bottom-up approach, with the separation of the complex control problem into several smaller simple problems, also leads to simplifications in debugging and maintenance of the system (Leitao, 2009).

However, there are also some barriers in the application of agent-based solutions mainly in their costs for implementation in comparison to the classical centralized solutions. Also no guarantee of operational performance can be made due to the emergent behaviors of the agents. Furthermore, the scalability of this technology is limited to the capabilities of the available industrial communication technologies. Moreover, certain standards and platforms are required for the interoperability of agent-based systems (Marik & McFarlane, 2005).

3.3.2 Data Quality

According to the quality-guru Juran (1989) data are of high quality if, *"...they are fit for their intended uses in operations, decision making and planning."* However, many databases contain a surprisingly large number of errors. This poor data quality has substantial social and economic impacts (Wang & Strong, 1996).

In POM there is a distinction between mainly two different types of data: master and transactional data. Master data describe the people, places, and things that are involved in an organization's business. Transactional data describe an internal or external event or transaction that takes place as an organization conducts its business (McGilvray & Thomas, 2008). Examples for master data include supplier, customer and material related data as well as bill of materials, work plans, operations calendars, resources, and so on. Examples for transactional data include sales orders, purchasing orders, inventories, invoices and so on. Both types of data require high data quality to ensure the efficient execution of business processes.

Especially, the broad advent of computer science in the 90's lead to the research in data quality, often also called information quality, due to problems in the definition, measurement and improvement of the quality of data in databases (Batini & Scannapieca, 2006). At that time the information systems success was also examined by DeLone & McLean (1992) coming to the finding that the system quality as well as the information quality form the backbone of the overall success. In the definition of data quality, the concept of the fitness for use of the data by data consumers is often used. Wang & Strong (1996) classify the dimensions of data quality in four categories: intrinsic, contextual, representational and accessibility data quality. The intrinsic data quality also includes, beside the traditional viewed accuracy and objectivity, believability and reputation. The contextual data quality highlights the requirements that data quality must be considered within the context of the task at hand. One approach for that is to parametrized the contextual dimensions for each task needed by the data consumer. The representational data quality emphases aspects related to the format and meaning of data. Finally, the accessibility has also to be taken into account (Wang & Strong, 1996). According to Wang & Strong (1996) high quality data should be *"...intrinsically good, contextually appropriate for the task, clearly represented and accessible to the data customer"*. Other sources (Eppler, 2006; Scheuch, et al., 2012) use similar classifications and overall the timeliness and accuracy of data can be found in several descriptions.

However, data quality in industrial manufacturing gives a diversified view, which is far away from high quality data. Apel et al. (2010) give several reasons for the often poor data quality:

- Data capturing: e.g. typing error, shortage of time, misunderstanding, incorrect data sources
- Processes: incorrect disclosure of data
- Data corruption: non updated data
- Architecture: redundant storage of data, missing interfaces
- Data use: inappropriate ambiguous use of data
- Definitions: inappropriate definition of the data content or format

According to a German study (Schuh & Stich, 2013), the real-time widespread crosslinking of production data is so far only partially possible because of the currently large number of manual system bookings and written documentation. 57% of the small and medium-sized enterprises (SMEs) located in Germany still use written documentation for the feedback of inventory data from the shop floor. In large-scale enterprises, 39% still use manually written information flows which makes real time feedback impossible. The interviewed enterprises also agree to over 90% on that the integration of IT will make the information flow from the shop floor to the data consuming departments more transparent and would reduce manual tasks for data recording, transmission, handling and processing.

As a result of the poor data quality PPC decisions are often based on averages and estimates (compare Chapter 4.2), which results in inaccurate planning results. However, the advent of CPS in production with its accurate sensor technique represents a promising approach to provide the data real-time and in the required quality needed for a reliable PPC (Hering, et al., 2013). Especially due to the developments of RFID technology, the data quality of the records of inventory, the inventory inaccuracy is an often viewed topic in POM science (Kang & Gershwin, 2004). The inventory inaccuracy occurs when the inventory record, which is what is available according to the information system, does not match with the actual physical inventory (DeHoratius & Raman, 2004). To protect against this issue and its negative impact on the performance of production planning and control, new methods and policies have to be developed which are more robust than the traditional one (Chan & Wang, 2014).

CHAPTER

4 Production Planning and Control

In preparing for battle I have always found that plans are useless, but planning is indispensable.
Dwight Eisenhower (1890 – 1969)

This chapter gives several definitions on the term production planning and control and the associated tasks. Furthermore, the different concepts of decomposition, aggregation and disaggregation are explained. Also the typical classification of production planning and control tasks along the time horizon is shown. Next, the existing planning approaches get explained and a more detailed description of the hierarchical planning approach and the used practices is given. In that respect forecasting, aggregate planning and master production scheduling get explained. Then the evolution of different production planning and control approaches such as material requirements planning and just-in-time manufacturing and others is given. Also a comparison of the two most common planning paradigms push and pull is given.

4.1 Definitions

The term production planning and control (PPC) consist of two main term which are: production planning and production control.

4.1.1 Production Planning

The APICS dictionary describes production planning as the following:

> *A process to develop tactical plans based on setting the overall level of manufacturing output (production plan) and other activities to best satisfy the current planned levels of sales (sales plan or forecasts), while meeting general business objectives of profitability, productivity, competitive customer lead times, and so on, as expressed in the overall business plan. The sales and production capabilities are compared, and a business strategy that includes a sales plan, a production plan, budgets, pro forma financial statements, and supporting plans for materials and workforce requirements, and so on, is developed. One of its primary purposes is to establish production rates that will achieve management's objective of satisfying customer demand by maintaining, raising, or lowering inventories or backlogs, while usually attempting to keep the workforce relatively stable. Because this plan affects many company functions, it is normally prepared with information from marketing and coordinated with the functions of manufacturing, sales, engineering, finance, materials, and so on. (APICS, 2013)*

A more general definition for planning is that planning can be understood as the intellectual anticipation of future events through systematic decision preparation and making. It includes a decision making process in which solutions of a problem are searched, evaluated and goal-oriented selected. This is done on the basis of a monistic or pluralistic objective function with monovalent or polyvalent expectations. (Kern, 1995)

Also certain tasks are related with the term planning (Koch, 1977):

- Definition of the objectives, actions and the needed resources
- Coordination of the objectives, sub-plans, actions and resources
- Initiate of the plan implementation
- Ensure establish reserves for the case of deviation from the plan

These tasks are executed in the planning process repeatedly until appropriate operational plans can be initiated. In the operational planning not all task-steps have to be run through, especially the objectives and resources are determined in the upstream strategic or tactical planning. The production planning task is therefore especially at the operational level a well-structured[48] problem, which can be solved by using a model of the system to be planned. (Dangelmaier, 2009)

According to Stachowiak (1973) a model is described by at least three characteristics:

- A model is always a model of something, namely image, representation of a natural or an artificial original that can be a model itself again.
- A model captures generally not all the attributes of the original, but only those that appear to the model creator relevant.
- Models are not clearly assigned to their originals. They perform their replacement function for certain subjects, within certain time intervals and restriction to particular mental or physical operations.

4.1.2 Production Control

Besides planning the term PPC also contains production control which is described by APICS (2013) as "*the function of directing or regulating the movement of goods through the entire manufacturing cycle from the requisitioning of raw material to the delivery of the finished products*".

According to Dangelmaier (2009) the control in PPC is dealing with the enforcement of a plan. While production planning itself has no feedback from the concerned production system, the production control can interact with the production system.

Especially in the German language there is a more precise separation on the general term control which would mean directly translated "Steuerung" while there is also the similar term "Regelung" with a different meaning. According to DIN (1968) the first term "Steuerung" is a process in a system in which one or more input variables influence the output values due regularities of the system. This describes the behavior of a typical input-output system also known as open loop control. Furthermore, the term "Regelung" is described by DIN (1968) as a process in which the controlled variable (output) is continuously recorded and

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[48] A well-structured problem consists of all elements of the problem including a well-defined initial state, a known goal state, constrained set of local state and constraint parameters. In addition, an algorithm exists which can determine an optimal decision within the time available. (Greeno, 1978)

compared with a reference variable (input). Corresponding changes result in an adjustment through a control variable in the sense of aligning the output to the reference variable. This behavior is also known as a closed loop control.

As the production control is more than a simple input-output system one should speak in the German language of a “Produktionsregelung”. However, as the practice is already used to the term “Produktionsplanung und -Steuerung”, it is maintained to this inconsistent term. (Kern, 1995)

4.2 Decomposition, Aggregation and Disaggregation

Decomposition refers to the separation of complex problems into manageable sub-problems. A prerequisite for such decomposition is that within the overall problem areas or elements with no or minor relationships in-between can be identified. A distinction between a horizontal and a vertical decomposition can be made. In the horizontal decomposition equal sub-problems are identified, while in the vertical decomposition, there is a hierarchical structure between the sub-problems. The decomposition of the total production planning task into isolated sub-problems allows the use of simple solution methods. However, the determined partial solutions must then be coordinated into an overall solution. (Steven, 1994)

Aggregation is a method of problem simplification through the meaningful grouping of data and decision variables. This approach results in several advantages such as the cost and time required for data retrieval can be reduced. Furthermore, aggregated numbers have a smaller variance than the individual values, so that prognoses are more reliable. In addition, by the use of a few aggregate values instead of many individual a better understanding of the basic relationships and influences can be achieved. Closely related to the concept of aggregation is the disaggregation, which is the backwards transformation of aggregated data to a desired level of detail. (Steven, 1994)

In PPC methods these problem simplification techniques are always applied in certain ways. According to Hopp & Spearman (2008) *"the first step in developing a planning structure is to break down the various decision problems into manageable sub problems".*

Dangelmaier characterizes planning systems by the following criteria (2009):

- Level of Detail refers to the accuracy of planning. A rough planning for example works with aggregated quantities in scope and time.
- Differentiation expresses the depth of the division into subsystems and their associated sub-plans. Planning tasks can be subdivided by function and time scope (long, short). The functional subdivision may result in sales, a production and procurement plan, which build upon each other in this sequence. The planning horizon and cycle characterizes the time scope subdivision.

Hopp & Spearman (2008) share this characterization by stating the following two premises which are used in PPC. First, problems at different levels of an organization require different levels of detail, modeling assumptions and planning frequencies. Second, planning and analysis tools must be consistent across levels.

The most important dimension on which planning systems are typically broken down is the time. The main reason for that is, that decisions within POM differ greatly along this variable which makes it essential to use different plan horizons in the decision making processes. The length of the planning horizons vary across different industries but can be typically divided into long, intermediate and short term. While long term planning activities have a horizon of a range of 1 to 5 years, an intermediate planning horizon ranges from a week to a year. Short term horizons can range from an hour to a week. (Hopp & Spearman, 2008)

Time Horizon	Length	Representative Decisions
Long term (strategic)	Year to decades	Financial decisions Marketing strategies Product design Process technology decisions Capacity decisions Facility locations Supplier contracts Personnel development programs Plant control policies Quality assurance policies
Intermediate term (tactic)	Week to year	Work scheduling Staffing assignments Preventive maintenance Sales promotions Purchasing decisions
Short term (control)	Hour to week	Material floor control Worker assignments Machine setup decisions Process control Quality compliance decisions Emergency equipment repairs

Table 4.1: Different time horizons with related decisions[49]

Table 4.1 shows the different planning decisions related to the time horizon. Long term, also called strategic decisions, basically consider questions such as, *"...what to make, how to make it, how to finance it, how to sell it, where to get materials,*

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[49] based on Hopp & Spearman (2008)

and general principles for the operating system" (Hopp & Spearman, 2008). Intermediate term, also called tactic decisions, determine *"...what to work on, who will work on it, what actions will be taken to maintain the equipment, what products will be pushed by sales, and so on"* (Hopp & Spearman, 2008). And finally, short term, also called control decisions, address the movements of material and workers, adjustments of processes and equipment, and actions needed to ensure that the system continues to work towards its goal.

These different planning horizons also imply different regeneration frequencies. In addition to that they also differ in the required level of detail as mentioned above. In general, it can be said the shorter the horizon the greater the amount of detail required in the modeling as well as in the data. (Hopp & Spearman, 2008)

Beside time there are also other dimensions on which PPC problems are broken down such as processes, products and people. As traditionally many operations are organized according the manufacturing process, it can be reasonable to separate the planning into the individual process steps. Another form of aggregation is to combine all products with a similar material routing. Typically, such combinations are called product families with the definition that within one family no significant setups are required but there may be setups between families. (Hopp & Spearman, 2008)

These separations of the decision problems along different dimensions are noting revolutionary but as it was also mentioned above there is a second premise which distinguishes a good from a bad system. The difference is not made in how the problem is broken into sub problems, it is made in how the sub problems are coordinated with each other (Hopp & Spearman, 2008). This means that long term planning must be well linked with intermediate planning and a similar link is needed between intermediate planning and short term planning.

4.3 Production Planning and Control Process

In the next chapters different planning approaches are explained and then the common type hierarchical planning is discussed in more detail.

4.3.1 Planning approaches

In PPC different modeling approaches exist. The most important are partial, total and hierarchical models.

Partial models solve the production planning problem in isolated, coordinated sub tasks. One form is the coordination of sub tasks in which the decisions are made isolated in a defined sequence, however, the subsequent subtasks take the results of already solved tasks into account. The flow of information is only in one direction. Due to the criticism of neglecting interdependencies in partial models, total models have been developed. Total models explicitly capture all alternatives in all periods, as well as all interdependencies and thus they can achieve an optimal solution. However, due the excessive usage of decision variables and restrictions, such total modes can only be solved for small PPC problems. Another approach is the use of hierarchical models, in which the overall planning task is decomposed into subtasks, which are based on the hierarchical structure of the planning problem. Through a few controlled interfaces the individual subtasks are coupled by placing requirements and restrictions from higher ordered planning results into the subsequent subtask. In case of deviations from the optimum in a subordinate problem a limited feedback into the next higher level can be carried out. (Steven, 1994)

Anthony (1965) was the first who recognized the hierarchical structure of the planning problem in production. Hax & Meal (1973) then analyzed the within practice always present hierarchical structure of production planning theoretical. Their basic model is based on the above mentioned levels of the planning hierarchy. The strategic planning is thereby required to be already completed. At the tactical level the rough planning of the production program is done and at the operational level, the detailed planning with the final determination of lot sizes is carried out.

Also related with the different model approaches is also the handling of dimension time. In total planning the entire decision problem can be solved in a single step. For this purpose, it is necessary that at the beginning of the planning period all relevant information is known or can be predicted. (Scholl, et al., 2003)

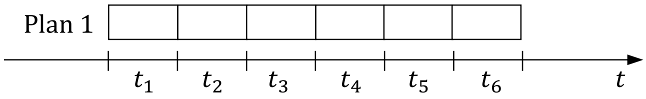

Figure 4.1: Total planning approach

Closely related to the total planning approach is the connecting planning. The infinite total planning period is thereby divided into non-overlapping, successive planning horizons. (Scholl, et al., 2003)

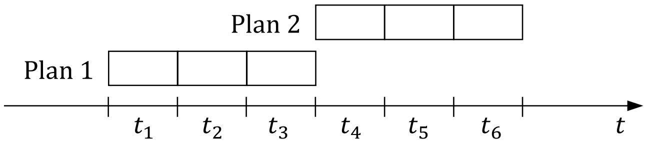

Figure 4.2: Connecting planning approach

The term rolling horizon planning refers to a procedure in which only the first period is planned fixed, all the other periods are tentatively scheduled. At the beginning of each period t the data is updated and the planning horizon is shifted by one period. (Scholl, et al., 2003)

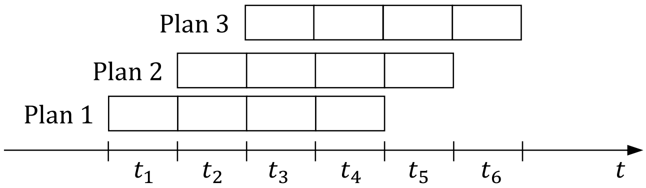

Figure 4.3: Rolling horizon planning

Figure 4.3 gives an example of a rolling horizon planning with 4 periods. The first plan considers period t_1 until t_4 while then in the next plan the period t_2 until t_5 are scheduled. This principle of rolling horizon planning is also generally used in hierarchical planning models.

4.3.2 Hierarchical Process

The PPC process is typically supported by forecasting in several stages. Forecasting is the process of making predictions about future values or events, in PPC mostly upcoming demand. Long term strategic resource planning deals with the planning of the capacity/facility and the workforce. The long rage demand forecast is used to make decisions on the need of physical equipment and on hiring, firing, training and so on. Furthermore, the capacity/facility planning includes make-or-buy decisions. In the medium range aggregate planning, the production is planned on an aggregated basis for certain groups of items. In the short term the aggregated production plan is disaggregated into the master production schedule (MPS) with specific products to be produced in particular time periods. Afterwards, in the scheduling and sequencing the individual production jobs get assigned to resources. The production control acts then as a feedback loop from the actual production execution to the upper levels.

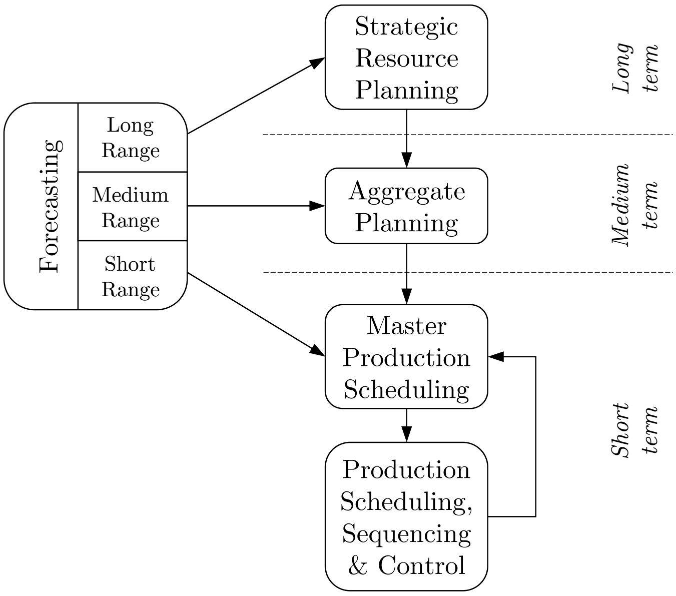

Figure 4.4: Generic hierarchical PPC process[50]

4.3.3 Forecasting

The starting point of all PPC systems is forecasting. This is true for make-to-stock (MTS) manufacturers as well as for make-to-order (MTO) manufacturers. The only difference between these types is the buffer used against demand uncertainty. In MTS systems, an inventory buffer is used while MTO systems hold safety capacity or use a time buffer. However, both manufacturing systems need forecasting models to predict future demand. If there is no further information shared between customer and manufacturer, forecasting tries to understand the past demand by identifying and quantifying patterns and factors.

However, even with the best forecasting model some uncertainties still remain, which lead to the following laws of forecasting by Hopp & Spearman (2008):

1. *Forecasts are always wrong.*
2. *Detailed forecasts are worse than aggregate forecasts.*
3. *The further into the future, the less reliable the forecast will be.*

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[50] based on core elements of the production decision making framework from Silver et al. (1998) and the production planning and control hierarchy for pull systems from Hopp & Spearman (2008)

These laws imply that perfect prediction of the future is not possible. Furthermore, the concept of variability pooling (aggregation) is a useful approach in forecasting. And finally the further the forecast goes into the future the greater the potential of changes is. Overall the main goal in forecasting is to minimize the difference between the predicted and the real values (forecasting error).

Forecasting is a large science field with many different approaches, nevertheless a basic distinction can be made between qualitative and quantitative forecasting (Hopp & Spearman, 2008).

Qualitative Forecasting

Qualitative forecasting methods use the expertise of people rather than mathematical models. Those approaches are used if no historical data is available, for example the introduction date of a new product. A structured qualitative forecasting method is the Delphi method, which was developed to estimate the number of atomic bombs required to reduce the munitions output by a prescribed amount. The Delphi method uses repeated individual questioning of experts through interviews or questionnaires to avoid direct confrontation of the experts with one another. In this multistep approach information from the experts is gathered and shared to the other experts in the next round. If the purpose is the estimation of a numerical quantity the individual estimates will show a tendency to converge even if the views are initially widely diverged. (Dalkey & Helmer, 1962)

Quantitative Forecasting

Quantitative forecasting methods are based on mathematical models which predict the future by using historical data. There are two groups of models, causal models and time series models. Causal models try to predict a future parameter (e.g. demand of a product) as a function of other parameters (e.g. grows of GDP, spending in marketing). A common technique used in causal models is regression analysis. Time series models try to predict future parameters (e.g. demand of a product) as a function of past values of that parameter (e.g. historical demand). (Hopp & Spearman, 2008)

According to Silver et al. (1998) a time series is composed of the following five components: (a) level, (b) trend, (c) seasonal variation, (d) cyclical movements and (e) irregular random fluctuations. The level captures the scale of a time series. The trend identifies the rate of grow or decline over the time. Seasonal variation can arise from natural forces or from human decisions and refer to a periodic variation of a fairly constant shape. Cyclic variation captures increases and decreases due to business cycles. Irregular fluctuations are the residue that remain after the effects of the other four components are identified and are removed from the time series.

In time series forecasting many different models exist. The most basic one is the moving average model, which computes the forecast of the upcoming period as the average of the last m observations. While in the moving average model all m periods are weighted equally, there are also weighted average models. In exponential smoothing all past observations are weighted using an exponential model. However, these both models assume no trend in the data. There are also further techniques such as exponential smoothing with a linear trend which also computes a smoothed trend in the data. Furthermore, there is also the Winter's method which adds seasonal multipliers to the exponential smoothing with linear trend model. (Hopp & Spearman, 2008)

4.3.4 Aggregate Planning

Once the upcoming demand is forecasted and the available resources are determined the aggregate plan can be generated. As different operations have different priorities and characteristics, aggregate planning also differs from plant to plant. In many operations the main issue is the timing of the production. In that case, the balance between costs for production and for inventory holding by still meeting the forecasted demand has to be met in aggregate planning. Also, decisions on staff additions or overtime as well as staff reduction can be made.

Hax & Meal (1973) formulated a linear programming (LP) model for this specific problem in their hierarchical production planning and control basic model. They used the prior mentioned aggregation of items to product families with no or just minimal setups within. They formulated the seasonal planning model using the following notation:

$R_{i,t}$ = hours of regular production of product family i to be scheduled during time period t

$O_{i,t}$ = hours of overtime production of product family i to be scheduled during time period t

$(R)_t$ = total hours of regular production available during time period t

$(O)_t$ = total hours of overtime production available during time period t

$I_{i,t}$ = inventory of product family i on hand at the end of time period t (units)

r_i = production rate for product family i (units/hr)

$D_{i,t}$ = forecasted demand of product family i during time period t (units)

$CO_{i,t}$ = costs of overtime production of product family i during time period t (€/hours)

$CI_{i,t}$ = inventory holding costs of product family i during time period t (€/unit-period)

$SS_{i,t}$ = safety stock required for product family i at the end of time period t (units)

Using this notation the objective of the seasonal planning model is to minimize the total of regular and overtime production costs and inventory holding costs by

$$min \sum_i \sum_t \left(CO_{i,t} O_{i,t} + CI_{i,t} I_{i,t} \right) \tag{4.1}$$

with subject to the following constraints:

$$\begin{array}{rcll} \sum_i R_{i,t} & \leq & (R)_t & for\ all\ t \\ \sum_i O_{i,t} & \leq & (O)_t & for\ all\ t \\ r_i * \left(R_{i,t} + O_{i,t} \right) - I_{i,t} + I_{i,t-1} & = & D_{i,t} & for\ all\ i,t \\ R_{i,t} & \geq & 0 & for\ all\ i,t \\ O_{i,t} & \geq & 0 & for\ all\ i,t \\ I_{i,t} & \geq & SS_{i,t} & for\ all\ i,t \end{array}$$

The above LP model determines the production and the stock for all product families so that production and inventory costs are minimized, with the constraints of the forecasted demand requirements. There is a distinction made between regular and overtime production because of the increase in labor costs when working overtime. The model then balances the tradeoff between overtime costs and inventory carrying costs to determine a cost optimal production plan.

However, in other operations the dominating issue can be the product mix or the production allocation in case of several production sides. Then, aggregate planning focuses on the profit optimized planning of how much of each product should be produced in each period with subjects to constraints in the demand, capacity and available raw materials. (Hopp & Spearman, 2008)

4.3.5 Master Production Scheduling

Out of the aggregate plan the master production schedule (MPS) is converted through disaggregation of the manufacturing output into the producible products. The MPS can be stated in specific end-item products or in options and modules which are later converted into specific products in the final assembly schedule (FAS). The stability of the MPS is an important measure for the performance of an operation. On the one hand, frequent changes can reduce productivity and are costly. On the other hand, too few changes can lead to poor customer service and increase inventory. Typically frozen time periods are used in the MPS to increase the stability. During this period no changes in the MPS are possible. Another concept is the time fencing in which for different types of changes specific periods are set in which this changes can still be handled. (Vollmann, et al., 2005)

For the planning and control of the low-level items needed for the finished good different approaches exist. In MRP the MPS provides the input data (gross requirements) which is then used to calculate the depending requirements of the low-level item by exploding the bill of material. The material and the centralized information flow of a MRP production system can be seen in Figure 4.5.

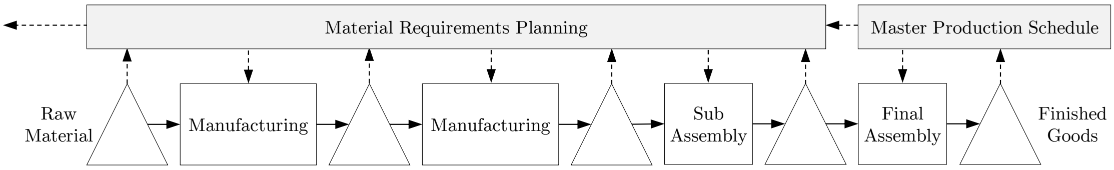

Figure 4.5: Material and information flow in a MRP production system

In a JIT production system, the information flow is decentralized and the production of low-level items is authorized through the removal of material of the intermediate stocks. The material and the decentralized information flow of a JIT production system can be seen in Figure 4.6.

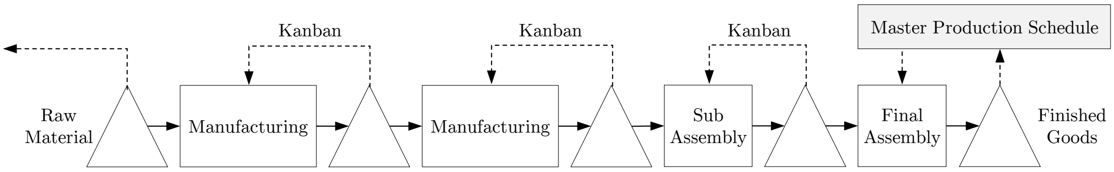

Figure 4.6: Material and information flow in a JIT production system

In the next chapter a more detailed explanation of the existing PPC systems is given.

4.4 Evolution of PPC Systems

Since the early days of industrial revolution PPC systems have been existing. As mentioned in Chapter 2.2.1, foreman ruled the shop floor at that time by planning and controlling the production, material ordering and shipping. With the development of the scientific management and Gantt's charts, the planning and control processes got more standardized. At that time simple reorder point (ROP) systems were used to control inventory. During the mid-1960s, computerized material requirement planning (MRP) systems slowly replaced the ROP system as the inventory control system of choice. Later on, these systems were further developed to manufacturing resource planning (MRP-II), manufacturing execution systems (MES) and finally enterprise resource planning systems (ERP). Meanwhile in Japan the ROP system was developed to a higher level in the Toyota production system (TPS) with its just-in-time (JIT) production. Followed by the quality focus in the total quality management (TQM) movement. Through the case study *The Machine That Changed the World* by Womack & Roos (1990) the Japanese's concepts then got famous under the name lean manufacturing.

Figure 4.7 show a rough time classification of the individual PPC evolution steps.

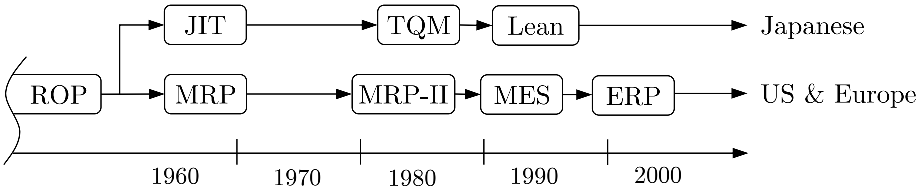

Figure 4.7: Evolution of PPC Systems[51]

In the next chapters a more detailed explanation on ROP, MRP and JIT systems is given.

4.4.1 Reorder Point Systems and Economic Order Quantity

After World War II, inventory was controlled using reorder point system (ROP) (Hopp & Spearman, 2008). Thereby certain replenishment policies were used to release orders based on the actual inventory level. Replenishment policies give and answer to the following questions (Silver, et al., 1998):

- How often should the inventory status be determined?

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[51] based on dates from (Rondeau & Litteral, 2001) and (Hopp & Spearman, 2004)

- When should a replenishment order be placed?
- How large should the replenishment order be?

Table 4.2 shows the four main replenishment policies using the dimension review and order quantity.

	Order Quantity	
Review	fixed	variable
periodic	*R,Q*	*R,S*
constant	*S,Q*	*s,S*

Table 4.2: Replenishment policies[52]

The *R,Q*-policy mean that after a fixed period of time *R* a fixed quantity *Q* is ordered. Typically, the amount *Q* is the economic order quantity (EOQ). The *R,S*-policy also reviews the inventory in fixed periods of time *R* but the ordered quantity *S* is not fixed. In this so called order-up-to policy, the difference between the inventory level and a desired level *S* is ordered. The *s,Q*-policy is reviewing the inventory constantly and in case that the inventory drops below a certain defined reorder level *s* a fixed quantity *Q* is ordered. In the *s,S*-policy the inventory is also constantly monitored. As soon as the inventory drops below the reorder point *s* the difference to a desired level *S* is ordered.

Economic Order Quantity

The EOQ is the order quantity that minimizes the total inventory holding costs and the ordering costs. It is one of the oldest classical production scheduling models. The model was developed by Ford W. Harris in 1913 and is also known in German-speaking areas as the Andler formula because it was advertised by Kurt Andler in 1929. Harris (1913) wrote in his paper *How many Parts to Make at Once* the following:

> *Interest on capital tied up in wages, material and overhead sets a maximum limit to the quantity of parts which can be profitable manufactured at one; set-up costs on the job fix the minimum. Experience has shown one manager a way to determine the economical size of lots. (Harris, 1913)*

In the formulation of the EOQ Harris made, the basic tradeoff between costs for setup and costs for inventory keeping. To derivate a lot size formula he made the following assumption:

- There is no capacity limit and the entire lot is produced simultaneously.

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[52] based on the inventory decision rules by Vollmann et al. (2005)

- The demand is deterministic and constant over time.
- Regardless of the size of the lot or the status of the production, the costs for setup are the same.

As he assumed a constant demand over the time, the inventory level results in the half of the order quantity Q. The holding costs are therefore the holding costs for inventory h times the average inventory level, which is the first term in the equation. Furthermore, by assuming fixed costs for ordering A and for a given annual demand D we must place D/Q orders we come to the second term. The last term then considers the unit costs c for producing one piece. There the total annual costs are

$$Y(Q) = \frac{h\,Q}{2} + \frac{A\,D}{Q} + c\,D \tag{4.2}$$

Figure 4.8 shows the three terms of (4.2) in costs per unit in a graphical way. Thereby, we can see a cost minimum at Q^* which is the EOQ or also known as the economic lot size. In addition to the mathematical optimum, the chart also shows that the sum of holding and setup costs is fairly insensitive to the order quantity around Q^*. (Hopp & Spearman, 2008)

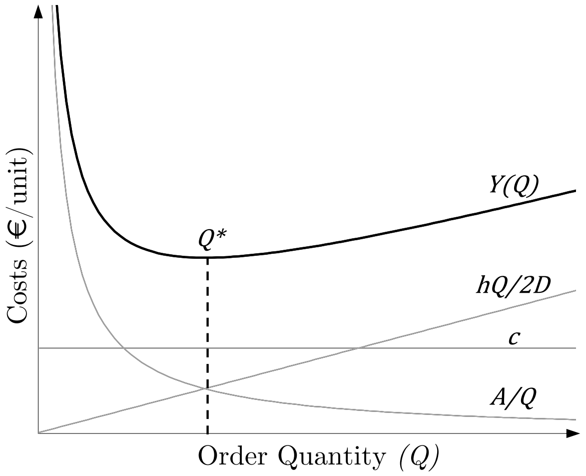

Figure 4.8: Costs in the EOQ model

The optimal order quantity Q^* can obviously be calculated by taking the derivate of $Y(Q)$ and setting the result equal to zero. This results then in

$$Q^* = \sqrt{\frac{2\,A\,D}{h}} \tag{4.3}$$

The original EOQ formula has been extended in various ways over the years. Thereby the assumption Harries made got more and more relaxed. For example the Wagner-Within procedure can be used for dynamical lot-sizing where the demand is not constant. The Silver-Meal heuristic tries to identify setup points by including demand figures one by one, which is more effective but the found solutions are not always optimal. (Hopp & Spearman, 2008)

4.4.2 Material Requirements Planning

According to Jelinek & Goldhar (1984) probably no other factor than information technology changed the basis of PPC through the automation of many clerical tasks and thereby improve manufacturing accuracy, reliability and predictability.

In the early 1960's the use of computer increased and many companies used digital computers to perform accounting. At that time Joseph Orlicky, Oliver Wight, and George Plossl along with others developed a new system which came to be called material requirements planning (MRP). Obviously they believed that they created something big as Orlicky (1975) titled a book concerning MRP as *The new Way of Life in Production and Inventory Management.* Also the APICS believed in the benefits of MRP and launched its *MRP Crusade* followed by several implementation of MRP in the American industry. (Hopp & Spearman, 2008)

The basic function of MRP is as its name reveals the planning of material requirements. Thereby, MRP deals with two basic dimensions: quantities and timing. An MRP system determines the production quantities and the production timing of all types of items from final goods to raw material. For that, in an MRP system the time as well as the demand are divided into so called buckets. A bucket is a discrete chunk typically of the size of one week or day. According to Dangelmaier (2009), two basic representations of the time are possible: big and small bucket models. Figure 4.9 show, an example with two workdays using these different modelling approaches. While in the big bucket model the time horizon is split up by full days, the small bucket model is representing the time with an hourly bucket size.

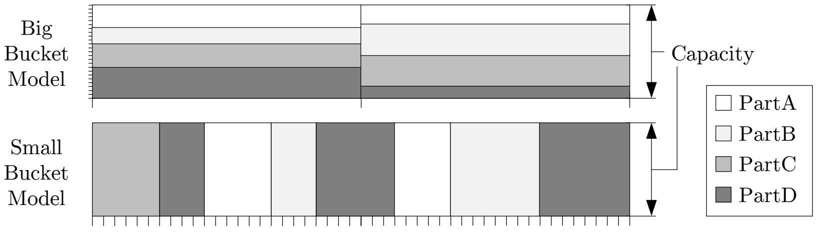

Figure 4.9: Big and small bucket models[53]

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[53] adapted from Dangelmaier (2009)

In a big bucket model more than one activity can be done in one time bucket while in a small bucket model only one concrete activity per time bucket is possible. This leads to the circumstance that in a big bucket model no concrete sequence for the individual activities within a time bucket is defined while in a small bucket model the sequence of actions over the time is well defined. Another key difference is the model accuracy regarding the lead time. In the big bucket model the lead time has often to be rounded up to the next full digit time bucket size which is often a day or a week leading to high WIP. Common examples using a big bucket modeling approach is the capacitated lot sizing problem (CLSP) and for the small bucket modeling approach the discrete lot sizing problem (DLSP). (Dangelmaier, 2009)

The demand that accumulates in an interval is then considered to be due at the beginning of the bucket. The bill of material (BOM) is used to describe the relationship between finished goods (end items) and lower-level items. (Hopp & Spearman, 2008)

Procedure

The basic MRP procedure is simple (Hopp & Spearman, 2008):

- Netting: determine the net requirements
- Lot sizing: divide the netted demand into appropriate lot sizes
- Time phasing: determine start times shifting the jobs by the lead times
- BOM explosion: generate gross requirements of the next item level
- Iterate: repeat all steps until all item levels are processed.

		Time Buckets (e.g. Weeks, Days)							
Part A		1	2	3	4	5	6	7	8
Gross requirements		15	20	50	10	30	30	30	30
Scheduled receipts		10	10		35				
On Hand Inventory	20	15	5	-45	25	-5	-35	-65	-95
Net requirements				45		5	30	30	30
Planned order receipts				60			60		60
Planned order releases			60			60		60	

Table 4.3: Example of the basic MRP procedure

Using the example of Table 4.3 the MRP procedure is explained in more detail. Therefore, the following notation is used:

D_t = Gross requirements (demand) for period t

S_t = Quantity currently scheduled to complete in period t

I_t = Projected on-hand inventory for the end of period t

N_t = Net requirements for period t

First the projected on hand inventory have to be calculated. For that the current inventory I_0 must be known. Then the projected-on-hand can be calculated with

$$I_t = I_{t-1} - D_t + S_t \tag{4.4}$$

By subtracting the gross requirements D_t and adding the already scheduled receipts from the previous on-hand inventory I_{t-1} the next projected on-hand inventory I_t can be calculated. Some MRP systems consider in that respect adjusted scheduled receipts if the current due date of the scheduled receipts is different to the plan. Next, the net requirements can be computed as

$$N_t = min\{max(-I_t, 0), D_t\} \tag{4.5}$$

These net requirements are then used in the lot sizing procedure. There exist several lot sizing rules used in MRP. The simplest rule is known as lot-for-lot (LFL), which states that the amount to be produced is equal to the period's net requirements. This rule is simple and follows the just in time philosophy, however it is not considering a tradeoff between setup and inventory holding costs. Another lot-sizing rule is the use of a fixed order quantity (FOQ), for example the EOQ. Moreover, a fixed order period (FOP) rule can be used. Thereby, in predefined periods, the whole accumulated net requirements are planned until the next fixed order period. Beside this basic rules, many other more advanced rules exist with the overall goal of a cost optimal schedule. Next, the planned order receipts get shifted by the planned lead time. Here MRP systems assume that the time to make a part is fixed, although some systems allow that the planned lead time is a function of the job size. In the last two steps then, the BOM is used to transfer the planned order releases as the demand for all depending lower level items of the just calculated item and rerun the MRP procedure until there are no lower level items left. (Hopp & Spearman, 2008)

Dealing with Uncertainties

As this above logic of MRP is deterministic, we need something that considers uncertainty and randomness. There are several sources of uncertainty. First of all, only in pure make-to-order systems the demand quantity and the timing is exactly known. In all other production systems, these values are only known by a certain forecasting reliability. Moreover, machine breakdowns, quality problems, yield losses and other uncertainties infect the production quantity and timing. To protect against these issues, safety stock and safety lead times can be used. Clearly both approaches increase inventory. Silver et al. (1998) provide the following guideline for copying with uncertainty in MRP. In their opinion, safety lead time should only be used for raw materials. They suggest to use safety stock:

- for items with direct external usage,
- for items produced by a process with significant variable yield,
- for items produced at a bottleneck operation
- and in semi-finished items which are used for myriad end-items.

Buzacott & Shanthikumar (1994) give a similar answer on the question of using safety stock or safety lead time. They concluded that safety lead time is only preferable to safety stock when it is possible to make accurate forecasts demands. Otherwise safety stock is more robust in dealing with uncertainties.

Weaknesses

However, there are even more challenges in MRP. According to Hopp & Spearman (2008) the three major ones are (a) long planned lead times, (b) capacity infeasibility of MRP schedules and (c) system nervousness. Silver et al. (1998) gives a more detailed overview of significant drawbacks such as the long planned lead times of MRP:

- Lead times: MRP is treading the lead time as an attribute of the part and not by the status of the shop floor. This means that whether a department is heavily loaded or underutilized the lead time assumed in MRP is the same. Therefore, typically lead times are inflated to avoid schedule problems, which increases obviously the WIP.
- Lot sizes: Optimal multi-level, multi-item lot sizing is extremely difficult. Therefore, MRP relies on heuristics which were already mentioned above. However, in most of the MRP systems, only the basic lot sizing rules LFL and EOQ are implemented.
- Safety stock: As typically MRP systems do not automatically support the calculation of safety stocks, these values are set by users which have typical little knowledge on appropriate safety stock levels.
- Incentive for improvement: Another primary weakness of MRP is directly related with the previous three. Because of the excessive effort to gather all input data such as safety stock, lead times, lot sizes, and so on, people tend to not to make any changes on these values. Typically for the installation of a MRP system is that it is desirable to inflate all these values to avoid startup problems. However, there is little incentive to dig through a well working system to change the values to more optimal one afterwards.
- Data consistency: Also a major benefit of MRP is the needed data accuracy and consistency because an operation must take control of inventories and schedules. However, in practice consistency of the data needed for planning is a common problem within MRP systems.

The basic MRP procedure assumes that all lines have infinite capacity, which typically creates problems when production is running near to the capacity limit. Therefore, the basic MRP procedure was later on extended to rough cut capacity planning (RCCP) and capacity requirements planning (CRP), which can be both often found in the further development of MRP the manufacturing resource planning (MRP-II). (Hopp & Spearman, 2008)

System Nervousness

However, one last problem is still there: the so called system nervousness which refers to the effect that minor changes in the master production schedule can results in significant changes in the planned order releases (Hopp & Spearman, 2008). The MRP system nervousness was first identified by Steele (1975) who listed several causes such as MPS changes, unexpected changes in previously made customer orders, parameter changes (e.g. lead time, safety stock), forecasting changes, vendor plant fall-down, scrap and spoilage, engineering changes, record errors and unplanned transactions for this issue.

For example, a demand increase by one piece can lead by an EOQ lot sizing policy to the production of a further full lot. Clearly, if we use a LFL policy there will be no larger changes, however this rule typically leads to many setups. In a guideline to reduce nervousness in MRP system by Vollmann et al. (2005) also the influence of the selection of an appropriate lot sizing policy is emphasized. They suggest to use different lot sizing rules for different item levels. One approach is to use at the top level EOQ, at the intermediate levels either EOQ or LFL and at the bottom level FOP policies (Vollmann, et al., 2005).

Another way to reduce nervousness is to reduce the changes in the input itself by freezing the early part of the master production schedule. By using such a frozen zone at the beginning of the planning horizon, stability can be introduced into the MRP system and the problems caused by nervousness can be reduced. A similar concept is to use firm planned orders in MRP to stabilize planning. (Vollmann, et al., 2005)

Also the updating frequency is a key determinant of the effectiveness of an MRP system. On the one hand, if we plan too often, the shop floor will be constantly flooded by changing planned order releases, on the other hand if we plan too infrequently we could end up with out of date plans. (Hopp & Spearman, 2008)

4.4.3 Extensions to Material Requirements Planning

Over the years, the basic MRP system got enhanced to avoid some of its main weaknesses. The following evolution steps were the extension of capacity planning in manufacturing resource planning (MRP-II), the integration of the shop floor control in manufacturing execution systems (MES) and finally the linking of serval operations in an enterprise with the enterprise resource planning (ERP) systems.

Manufacturing Resource Planning (MRP-II)

As its predecessors, MRP-II also started with a promising book title *MRP-II: Unlocking America's Productivity Potential* (Wight, 1981). MRP-II added capacity requirements planning (CRP) capabilities to create a closed-loop PPC system. Now with MRP-II it was possible to integrate material and capacity requirements and constraints in the calculation of the overall production plan.

CRP calculates the needed capacity through time at each resource by a given MPS. First a rough cut capacity planning (RCCP) is sometimes performed to evaluate a tentative MPS. The RCCP is less detailed than the CRP and provides a quick capacity check of a few critical resources to ensure a feasible MPS. The second more common type is the CRP in which the MPS is exploded through MRP. Using the routings of all the individual items the planned order releases are translated to capacity requirements (for example in machine hours) for each time bucket and resource. In infinity loading the capacity constrains are ignored and capacity profiles are calculated. In finite loading the orders are planned considering the capacity constraints. (Vollmann, et al., 2005)

Manufacturing Execution Systems (MES)

In the late 1980's, with the start of the time-based competition, the nature of manufacturing got more and more dynamic. Processes and products changed weekly and production schedules even changed on a daily or hourly basis. MRP-II systems required a high degree of human intervention to create proper plans and ways to better manage the execution of the shop floor activities were needed. This was the birth time of manufacturing execution systems (MES) which generate an interface between MRP-II and the shop floor. While MRP-II is described as a closed loop PPC system, MRP-II with MES can be seen as a continuous loop PPC system. Also, information technology was a main driving force in this integration with the development of automatic identification and data-collection systems. Bar code readers, radio frequency transponders (RFID) and other technologies replace people or reduce the chance of making errors in the data collection. Also low-cost personal computers, relational databases, local area network technology and open system standards supported this trend. (Rondeau & Litteral, 2001)

Enterprise Resource Planning Systems (ERP)

According to Hopp & Spearman the further development was the following:

> *MRP-III never quite caught on, nor did the indigestibly acronymed BRP (business requirements planning). Finally, in spite of its less than appealing acronym, the enterprise resource planning (ERP) emerged victorious. (Hopp & Spearman, 2008)*

This was primarily due to the success a few vendors (e.g. SAP) had in the integration of several operations such as distribution, accounting, financial, personal and so on in a whole product. This success of ERP was then mainly supported by three developments. First of all, the supply chain management (SCM) trend, which extended the traditional inventory control methods over a wider scope including distribution, warehousing and multiple production locations. Second, the business process reengineering (BPR) movement which led companies to rapidly change their evolved management structures to fit a software package. And third, the cheap availability of personal computers. (Hopp & Spearman, 2008)

Advanced Planning Systems (APS)

As it is well known that the strength of ERP systems is not in the area of planning, advanced planning systems (APS) have been developed to fill this gap. They are based on the principles of hierarchical planning providing several solution approaches from mathematical programming and meta-heurists. (Stadtler, 2005)

As it can be seen in Figure 4.10, the focus of APS is to support the material flow across all related business functions: procurement, production, distribution and sales. Furthermore, APS offers several modules for all three levels of aggregation out of hierarchical planning.

Although this already sounds very promising, there are some drawbacks and deficiencies of today's APS. First of all, accurate demand forecasts are a very important input, hence great emphasis has been put in the development of forecasting techniques but sophisticated models for demand planning are still rare in APS. Second, the great integration of all SCM activities in the master planning led to very complex models and often a compromise between model detail and solution capabilities of the algorithm has to be made. (Stadtler, 2005)

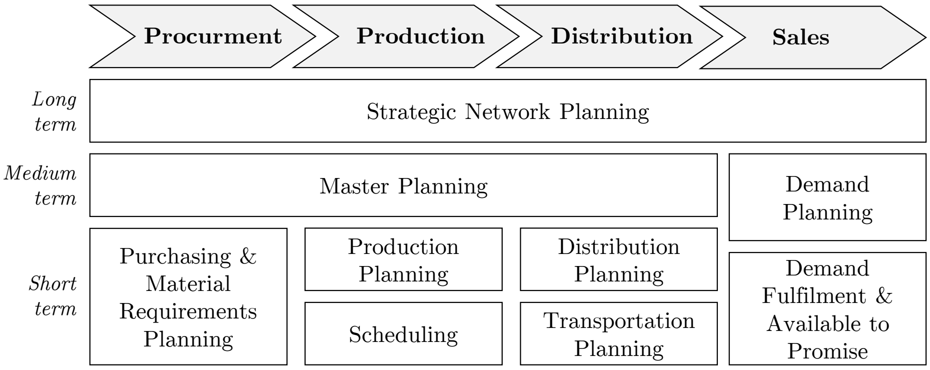

Figure 4.10: Typical modules of an APS software[54]

There is ongoing research in the area of event-based planning, which focuses on the updating frequency of the planning system. Nowadays most systems work with rolling horizons, however it seems that a reoptimization from scratch is neither necessary nor wise due to the system nervousness. Instead an even-based updating scheme might be more appropriate. Furthermore, so far only deterministic models are used and uncertainties are covered by safety stocks or times. Another approach dealing with uncertainties is the use of stochastic programming. However, since todays real world problems are already hard to solve with deterministic models, this seems to be out of reach for some time. Moreover, there is the questioning of the centralistic view of hierarchical planning in today's APS. As already discussed in Chapter 3.3.1 there is a trend to use decentralized agent technology for the computation of production plans. Thereby, the overall decision problem is divided into subtasks which are then solved by software agents which communicate and coordinate their decisions among each other. (Stadtler, 2005)

4.4.4 Just-in-Time and Lean

Contrary to the development of computerized inventory management systems in the United States the evolution of PPC in Japan went in a completely different direction.

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[54] based on (Stadtler, 2005)

Just-in-Time

The roots of just-in-time (JIT) are deeply grounded in the Japanese cultural, geographical and economical background, which was mainly influenced by the very limited space and resources in Japan. After World War II Japan's economy was shattered and the productivity in comparison with the United States was by just one-ninth (Hopp & Spearman, 2008). One of the most influencing sources of JIT was Taiichi Ohno[55] at Toyota Motor Company. According to him the innovation journey of JIT began in 1945 when the president of Toyota demanded to *"...catch up with America in three years. Otherwise, the automotive industry of Japan will not survive"* (Ohno, 1988).

This set the motion of some fundamental changes in manufacturing management. Ohno closed the huge productivity gap to the United States by focusing on the elimination of waste. Moreover, he created a system which made the cost efficient production of many models in small numbers possible. The main challenge thereby is to maintain a stable flow of material in the varied production mix without having large inventory. Ohno addresses this challenge in the Toyota production system (TPS) which rests on two main pillars (Hopp & Spearman, 2008):

- Autonomation, or automation with a human touch
- Just in time, or producing only what is needed.

Autonomation refers to best practice methods in which machines are both automated, so that one worker can operate many machines at the same time, and fool proofed so that they automatically detect problems. For that, devises for quick dimension or quality checks so called *poka-yokes* are used to help workers to avoid *(yokeru)* mistakes *(poka).* These productivity improvements also help to avoid disruptions in the manufacturing environment and by that enables a smooth material flow. The second pillar is aiming at the goal that each workstation acquires the needed material from the upstream workstation precisely as needed or just in time. To achieve this goal a pristine production environment is necessary. (Hopp & Spearman, 2008)

Philosophy of JIT

According to Silver et al. (1998) the goal of JIT is *"...to remove all waste from the manufacturing environment, so that the right quantity of products are*

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[55] Taiichi Ohno (大野耐一) (1912 – 1990) is considered to be the father of the Toyota production system, which became lean manufacturing in the U.S.

produced in the highest quality, at exactly the right time (not late or early), with zero inventory, zero lead time, and no queues".

Waste for example means inventory, disruption, poor quality. In addition, JIT seeks to eliminate all uncertainties including machine breakdown. For this a company must establish a continuous improvement or as it is called *kaizen*. This dynamic stands in the contrast to the static behavior of MRP in which, once the numbers (e.g. safety stock, safety lead time) are entered, nobody feels responsible to change the running system.

Closely related to JIT is also the slogan zero inventory. In Chapter 2.3.2 it is already proofed that this catchphrase is not a realistic goal. However, there are even more confusing absolute ideals in the realization of zero inventory, which are obviously not more achievable in practice but may inspire the continuous improvement philosophy behind JIT. Edwards (1983) describes the following seven zeros:

- Zero defects: To avoid disruption, since there is no inventory which compensate a defective part, it is essential that parts are produced at the desired quality.
- Zero (excess) lot size: Since in JIT systems the goal is to replenish stock as it is taken, the lot sizes have to be small (lot size one) to avoid delays.
- Zero setups: As the common reason for big lot sizes is the setup time, eliminating changeovers is the premises for lot size one.
- Zero breakdown: As JIT systems run without excess WIP, outtakes cannot be buffered. Therefore, in ideal JIT systems, unplanned machine failures are not tolerated.
- Zero handling: If the parts are made in exactly the quantity and at the times required, then the material must not be handled more than absolutely necessary.
- Zero lead time: In a perfect JIT flow a downstream workstation requires parts and they are provided immediately.
- Zero surging: In a JIT system the flow of material is smooth as long as the production plan is smooth. Sudden changes (surges) in the quantity or production mix cannot be handled and will lead to delays.

In the view of Toyota, the inventory is the main control variable to achieve these zero goals. Metaphorical, the inventory can be viewed as water that covers up problems that are like rocks (see Figure 4.11). Therefore, first of all the WIP inventory must be removed from the stockroom and put on the factory floor, where it is visible. Then in a continuous improvement process, the inventory is reduced step by step to expose problems and attention can be directed to their solution. (Vollmann, et al., 2005)

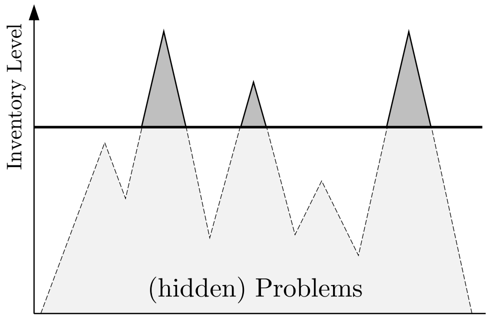

Figure 4.11: Toyota's view of inventory[56]

According to Vollmann et al. (2005) JIT is built out of four fundamental blocks: product design, process design, human/organizational elements and manufacturing planning and control. The activities in product design include quality, designing the products for cell manufacturing and reducing the number of BOM levels to as few as possible. The reduction of BOM levels is also closely related to the changes in process design. For fewer levels, the number of process steps can be reduced through process changes such as cellular manufacturing. Using a U-shaped layout, the machines are closely located to one other and workers can see and attend all machines with a minimum of walking. The third building block of JIT is the human/organizational elements which include continuous improvement, cross training, process improvement and so on. The main objective is continual learning and improvement because the knowledge of the workers is often a more important asset than the firm's equipment. The last block is dealing with production planning and control which involves according to Ohno (1988), two main components: kanban and level production.

> *Kanban is a tool for realizing just in time. For this tool to work fairly well, the production process must be managed to flow as much as possible. This is really the basic condition. Other important conditions are leveling production as much as possible and always working in accordance with standard work methods. (Ohno, 1988)*

Kanban

In JIT systems the amount of in process inventory between two workstations is controlled by the number of cards assigned to the pair of workstations. One single card, also called kanban card, is attached to a standard container. A kanban system is also called a pull system because the production is initialized at a given work center only when its output is needed at the next stage of production,

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[56] based on (Vollmann, et al., 2005)

whereas a push system implies that the work center produces based on a forecast regardless if the parts are immediately needed in the downstream material flow or not (Silver, et al., 1998). A more detailed definition on pull and push and its differences can be found in Chapter 4.5.

In a JIT production system, the kanban card represents the information flow. A card typically contains the following information (Silver, et al., 1998):

- kanban number (identification of a specific card),
- part number,
- name and description of the part,
- place where the card is used,
- number of units in the standard container.

The simplest kanban system is a single card kanban which is shown in Figure 4.12.

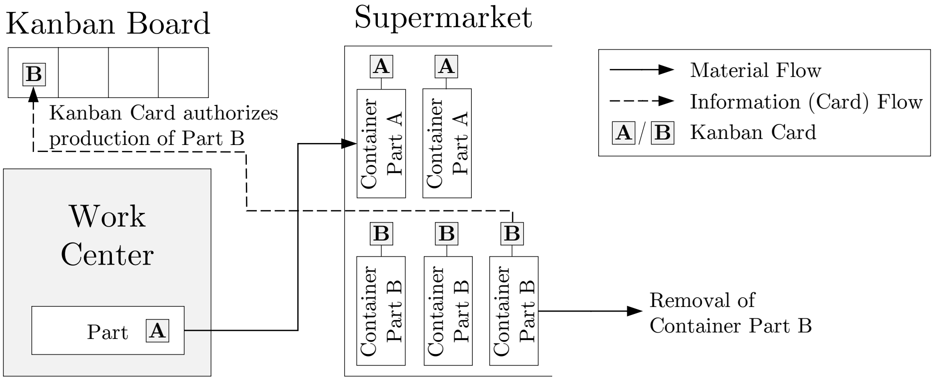

Figure 4.12: Single card kanban system

Thereby after the work center, the inventory is kept in a supermarket in which lots of the individual parts are stored in their standard container. The supermarket is organized in a way that the different types of parts are stored locally separated. To each container, a kanban card is assigned. When the downstream workstation needs parts, a container is removed from the supermarket. Subsequently the kanban card assigned to the container gets detached and moved to the work center's kanban board. On this board, all kanban cards with no container detached are kept and signal the work center to restock these items in the size of the standard container.

The amount of kanban cards needed between two work centers can be calculated using the following equation. This formula contains a factor α which includes safety stock, however Toyota remarks that this factor should be less than 10%. Also the container size should be kept small and standardized with around 10% of the daily requirements. (Vollmann, et al., 2005)

$$Kanban\ Cards = \frac{Demand \times Lead\ Time \times (1 - \alpha)}{Container\ Size} \tag{4.6}$$

Beside this single card kanban system also different variations exist. In the two card kanban system, there is a separation between production and move cards. In this case, there is in addition to the outbound supermarket as it is shown in the single card kanban system, an inbound supermarket in front of the work center. The move card authorizes the transfer of standard containers between the outbound stock point and the inbound stock point of the next work center. The production card, similar to the single card kanban approves, the production of a standard container of a specific part to replace the container just taken out of the outbound supermarket. (Silver, et al., 1998)

Another variation of kanban is the container kanban in which no cards are used. In such a system, an empty container authorized the production of the specific parts. Furthermore, signal kanban systems also require no cards. In such a case, reorder point levels of inventory are directly painted at the shop floor. There also exists electronically supported kanban (e-kanban) in which the card flow is replaced by an IT-system. Especially in the assembly lines of automotive industry, kanban is part of the material supply of a line. Thereby the cards act more as the above described move cards, because just the consumption driven transportation of parts from the central warehouse to the assembly line is controlled yet not the production of the parts. (Klug, 2010)

Heijunka

As mentioned in the zero goals, JIT needs a smooth production plan to work well. If volumes or product mixes change great in time, it will be difficult for workstations to replenish the parts just in time (Hopp & Spearman, 2008). This means, if multiple items are produced in the final assembly operation, it is required to develop a regular cycle among these items which ensure a smooth workload. This small cycle times, furthermore, avoid buildup of stock of finished goods and keep the customer response times short. (Silver, et al., 1998)

This stands quite in contrast to the conventional batch production. If the MPS requires a monthly production of 10.000 units within the 20 working days in a mix of 50% part A, 25% part B and 25% part C one would produce the first 10 days part A and then 5 days part B and finally the last 5 days part C. In a JIT system such a mixed model production looks significantly different. Thereby the products are sequenced in a smooth way such as

A-B-A-C-A-B-A-C-A-B-A-C-A-B-A-C...

to maintain a constant 50-25-25 mix over the time. (Hopp & Spearman, 2008)

A measure for the smoothness or flexibility of a production system is the every part every interval (EPEI) measurement. The EPEI of a production process is the sum of the processing time for all product variants in the respectively predetermined batch sizes plus the necessary setup times as well as planned and unplanned downtime. This value indicates how long it takes for the current conditions until all variants were produced once. (Erlach, 2010)

To achieve low EPEI values the lot sizes and moreover the setup times have obviously to be small. For that, JIT offers a further slogan called single minute exchange die (SMED) which stands for changeover times below 10 minutes (Hopp & Spearman, 2004). However, such achievements do not happen overnight. It took Toyota about 25 years to reach this SMED target. According to Ohno (1988) in 1945, the setup time on a large press was about 2-3 hours, by the 1960s it could be reduced to 15 minutes and in the 1970 they were down to 3 minutes.

Another concept related to leveling production is the takt time which is the average unit production time needed to meet customer demand. For the above example with the 10.000 pieces of demand in 20 work days, this would mean 500 parts per day. In a two shift operation with 480 minutes each shift this then results in a takt time of 1.92 minutes which is the desired pace of the whole production system. In reality, it will be unlikely to produce exactly one unit every 1.92 minutes. Here small deviations are no problem, in case of a lines falls back during one hour it will catch up in the next one. However, the difficulty lies in the dealing with unexpected disruptions such as machine breakdowns. One way to avoid a backlog is the use of so called two-shifting. Thereby, two shifts are scheduled per day which are separated by a down period. This down period can be used for preventive maintenance or to catch up a backlog. This use of the capacity buffer is an alternative to the inventory buffer used in most MRP. (Hopp & Spearman, 2008)

Out of the smooth production flow requirements of JIT, a separate movement rose which than ultimately become even larger then JIT itself. Hopp & Spearman (2004) wrote that total quality management (TQM) *"...grew into a popular management doctrine institutionalized in the ISO 9000 Certification process. The focus on TQM in the 1980's also spurred Motorola to establish an ambitious quality goal and to develop a set of statistical techniques for measuring and achieving it. This approach became known as Six Sigma..."*.

LEAN

Outside of Japan, the JIT system became recognized in the 1980s through the publishing of several books such as *Driving the Productivity Machine: Production* *and Control in Japan* by Hall (1981), *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity* by Schonberger (1982) and finally also Ohno (1988) published *Toyota Production System: Beyond Large Scale Production* in English. At that time companies already become attracted to the simple philosophy and the inherent techniques. However, depending on how creative and insightful the managers tying out JIT were it worked sometimes, sometimes not. According to Hopp & Spearman (2004) Ohno once claimed in an interview that Toyota considered the system so powerful that they used misleading terms and words to describe it. However, Toyota was also very open and invited the whole world to see their factories in the 1980s and 1990s. In 1990, after a 5 year MIT case study, the book *The Machine that Changed the World* published by Womack, Jones and Ross (1990) refreshed the ideas of JIT as lean management. The study compared several management techniques in the automotive industry in the United States, Europe and also Japan and concluded that the Japanese methods, especially those of Toyota, were absolutely superior (Hopp & Spearman, 2004). Under this new name, the simple techniques of Ohno got again into focus and with *"...the help of an army of consultants, lean became the rage"* (Hopp & Spearman, 2008).

Weaknesses

In addition to this incredible success story of JIT and lean weaknesses and warnings must also be mentioned. However, the probably most dominating notice is not really a weakness of JIT at all. It is rather the trend that, driven by the success story of Toyota and big promises of consultants, production manager implement JIT where it simply does not fit at all. According to Silver (1998) JIT does not fit in MTO production with high variability which also clearly appears from the JIT system properties.

> *JIT is for example not appropriate in job shop where products are made to order, variability is high, and demand is extremely nonstationary. Production is not smooth because bottlenecks shift continually. The high level of variability implies high level of inventory, but it is difficult to know exactly what inventory to put into the system when products are all made to order. (Silver, et al., 1998)*

Furthermore, Silver et al. (1998) mention that JIT does not fit to industries such as process industries where the stages of production are tightly linked. An interesting comparison for understanding the weaknesses of JIT is done by Karmarkar (1988). He compares the JIT pull principle with a fast food restaurant like McDonalds. There, a customer orders a hamburger and the server gets one from the rack. This then causes the cook to make new one if the number of hamburgers in the rack gets too low. This approach works perfectly fine if the franchise restaurant is downtown with a steady daily stream of customers. But if it is located next to a football stadium, such a pull system will create an extremely long queue when the game ends. In such a case, it would be better to push production according to a forecast.

According to Silver et al. (1998) other weaknesses are that JIT systems are through the low inventory levels, vulnerable to plant shutdowns, demand surges and other uncertain events. Furthermore, JIT cannot accommodate frequent product introduction and phasing outs. Finally, in the amazing success stories the improvements can not always be directly assigned to JIT programs alone.

4.4.5 Optimized Production Technology

Beside the MRP and the JIT evolution in PPC, there were also many other smaller trends. One remarkable one is called optimized production technology (OPT). Along with its principles called theory of constraints (TOC), it got popular through the book *The Goal: A Process of Ongoing Improvement* by Goldratt and Cox (1984). The views on some of the most important operating performances in OPT are different to MRP and JIT. In OPT, throughput is viewed as the rate at which a manufacturing firm sells finished goods. Inventory is the money the firm has invested in purchasing things which it intends to sell. And finally operating expense is the cost of converting inventory into throughput. However, the problem is that constraints hinder performance. As the name already says TOC focuses on constraints such as bottlenecks in production. Like the continuous improvement in JIT also OPT tries to establish an ongoing improvement process but the targets are bottleneck resources. Along with other rules, TOC addresses that *"...an hour lost at the bottleneck is an hour lost for the total system"* and *"...an hour saved at a nonbottleneck is a mirage"* (Silver, et al., 1998).

4.5 Push and Pull Principles

The development in POM and PPC is strongly driven by the use of buzzwords. Push and pull are just two examples of these that stand for different PPC principles which are commonly used in practice. Unfortunately, their definitions are not well defined and therefore they are often misunderstood.

> *The terms pull and lean production have become cornerstones of modern manufacturing practice. But, although they are widely used they are less widely understood. (Hopp & Spearman, 2004)*

Furthermore, especially in huge science fields such as POM new trends often create over-reaction.

> *Like all good revolutions, just in time manufacturing is producing revolutionaries who don't know when to stop. (Karmarkar, 1988)*

In this chapter the key differences between push and pull principles and their prominent realizations MRP and kanban get analyzed.

4.5.1 Definitions

First of all, the nature of push and pull systems in general have to be distinguished. According to Benton & Shin (1998), these terms have been used decades without clear definition and the use of MRP and JIT with its kanban as representative of push and pull system has created even more controversy. Therefore, they provide a good review on this topic showing three different ways how push and pull can be defined. The most common way to characterize push and pull system is in term of the order release. In this viewpoint, in a pull system, an order is triggered by removing an end-item, while in contrast in a push system the orders are generated by anticipation of future demand. This view is also shared by Karmarkar (1988). Another way to distinguish between push and pull is the structure of the information flow. In push systems, the information flow is centralized and information on customer orders and demand forecasts are used to release information for all levels of production. In contrast, in a pull system, the physical flow of material also triggers a local demand information. So in a pure pull system, the information flow is decentralized. However, using this straight forward separation the JIT production system also has push elements as the capacity of the standard containers and the number of kanban cards are calculated centralized. Finally, the third way to interpret push and pull system is the WIP level on the shop floor. Hopp & Spearman define a pull system as the following.

> *A pull production system is one that explicitly limits the amount of work in process that can be in the system. By default, this implies that a push system is one that has no explicit limit on the amount of work in process that can be in the system. (Hopp & Spearman, 2004)*

Benton & Shin (1998) conclude, out of this three viewpoints, that if the “*... material flow is initiated by the central planning system without controlling WIP level, this system is close to the pure push system.”* And furthermore *“...in a pure pull system the subsequent process will withdraw (i.e. pull) the parts from the preceding process using local information and controlling WIP inventory level.”*

This leads to the definition that at the shop floor level kanban is a pull system and MRP works as a push system. However, JIT also using push functions for example in the long term production planning and the master production planning. A further view on the definition dilemma is the origin of JIT and MRP. According to Matsuura et al. (1995) in Japan JIT is understood more as a philosophy, while MRP is a systematic top down PPC system.

As there rarely exists a pure push or pull production system in practice, many researchers have realized the possibility of a cohesion between push and pull principles. In so called hybrid approaches, the idea is that both principles have their own unique advantages and disadvantages. Through an integration, the advantages of both systems can be exploited to achieve better performance (Benton & Shin, 1998). Dickmann (2009) distinguishes in that respect between vertical hybrid approaches and horizontal hybrid approaches. In a vertical hybrid approach both principles are integrated redundantly with one other. One example for that is the CONWIP control developed by Hopp & Spearman which combines MRP (push) with a WIP cap (pull) using cards in a broadly similar fashion as kanban does. In a horizontal hybrid approach, the push and pull principles are used parallel for different product families. For example, for less valuable items kanban (pull) is used while for expensive highly customized parts MRP (push) controls the production.

4.5.2 Comparison Studies

Since the attention of the industry on JIT techniques several push/pull comparison studies have been made. Karmarkar (1988) recognized that the kanban system can also be seen as a simple s,Q system (compare the replenishment policies of Chapter 4.4.1). The reorder point s is the number of kanban cards and the order quantity Q is the size of a standard container. However, MRP can be viewed as an s,Q system as well. Axsäter & Rosling (1994) show that MRP is even more general than an s,Q-policy so that any s,Q system can be replaced by an MRP system. Silver et al. (1998) concluded out of that, that MRP dominates both, kanban and s,Q, because it is more general and can imitate either.

> *…JIT is not better for certain environment. For example, in multistage, system where end item demand fluctuates widely, the kanban system does not work well. Moreover, even when end item demand is relatively level, fluctuation in component requirements, can be caused by batching decisions that are made because of high setup times/costs. So if there are significant setup times, and parts are therefore batched for production, dependent demand will fluctuate widely and kanban and s,Q system will not be appropriate. A related reason is that if there are multiple items, and high changeover times between items, batching will be necessary. (Silver, et al., 1998)*

Therefore, kanban only applies in high volume lines where setup times are low, small lot sizes are used, and variability in demand is not amplified back through the system. But Silver et al. (1998) give additionally an answer to the question why JIT is then such an improvement on MRP. As already discussed, MRP is lacking in incentives for improvement. In the decentralized nature of the manual controlled kanban, improvements are far easier to implement, but that does not mean that MRP cannot fit into a continuous improvement environment.

One of the earliest and largest conducted analytical comparison studies of MRP and JIT was performed by Krajewski et al. (1987). In this study, a massive simulation based analysis of thirty-six factors that influence the performance of a production system was made. The factors were clustered into:

- customer influences, including forecast errors
- vendor influences, including vendor quality and lead time variability
- buffer mechanisms, including capacity and inventory buffers
- product structure, including BOM levels
- facility design, including routing pattern and length
- process, including scrap, breakdowns and worker flexibility
- inventory, including inventory accuracy and lot sizes
- as well as some other factors.

Thereby, Krajewski et al. (1987) concluded that changing these factors is more important than the used scheduling system.

> *The performance of kanban was quite impressive in our experiments. However, the natural question arises as to how much*

> *of this performance is attributable to the kanban system as opposed to the manufacturing environment in which it was applies... The reason why kanban appears attractive is not the system itself. A reorder point system does just as well. The kanban system merely is a convenient way to implement a small lot strategy and a way to expose environmental problems. (Krajewski, et al., 1987)*

So it is mainly the flow environment established through the JIT philosophy which makes the difference. However, there is no point that such an environment can be established and then run by an MRP system. However, Krajewski et al. (1987) also mention that as kanban is a paperless system, no excessive documentation with high administrative costs like in a MRP system is needed. Also other simulation studies for example Steele & Russell (1990) conclude that the JIT production environment with its small setup times and lot sizes is the critical factor for the superior performance of such a production system.

Spearman & Zazanis (1992) found out that it is not the pull principle itself, it is the limit in the level and variability of WIP inventory which leads to superior performance. Furthermore, they mention that *"push system control throughput by establishing a master production schedule and measure WIP to detect problems in meeting a schedule".* In contrast *"pull system control WIP and must measure throughput against required demand".*

Sarker & Firtzsimmons (1989) claim the possibility of a low utilization when the machines are not balanced perfectly as a potential problem of the pull system. Plenert (1999) found the same issue by analyzing labor efficiencies in push and pull system. He claims that JIT was developed in Japan during a time when resources and capital was limited and the unemployment was high. Therefore, the clear focus was on material efficiency and not on high utilization of labor or equipment.

According to Benton & Shin (1998) the *"difficulties in comparing MRP and JIT production systems originate from the fact that MRP was developed as a planning tool and kanban as a control device. The strength of MRP is in long range planning, scheduling, material planning and coordination... In contrast, JIT production systems are effective systems for the shop floor scheduling and to control. Thus the integration of MRP and kanban would allow firms to improve manufacturing effectivity and customer service level."* Therefore, in several hybrid approaches, MRP can be seen as the main planning tool, while kanban acts as the control mechanism on the shop floor. Benton & Shin (1998) state that there is no reason why centralized planning information should not be used in a

JIT production system. Otherwise kanban control mechanism can be used to execute the production plan in a MRP based manufacturing environment.

As mentioned in the weaknesses of JIT in Chapter 4.4.4 with the McDonalds example, pull principles have serious problems when the demand is fluctuating. According to Monden (1984) a kanban system is able to adjust to daily fluctuation of demand within ±10% deviations from the monthly production schedule. Also Hopp & Spearman (2008) point out that variations in the volume or the product mix destroy the flow and have serious influence on the performance of kanban. Krishnamurthy et al. (2000; 2004) performed several simulation studies with multiple products and changing product mixes. Their experiments showed that under that circumstances the look-ahead feature of push yields to better performance in terms of service level and average inventory and they concluded that a pure pull strategy requires more inventory in flexible environments. Especially, if the kanban card allocation is not set carefully in a pull system despite having high inventory, the system could suffer poor service level.

Barbey (2010) is also studying a similar problem and suggests a dynamically controlled system in which the kanban card amounts are adjusted by the expected demands. However, the benefit of the self-adjusting kanban system then gets lost. So this procedure is just another elaborating attempt to fit a non-matching PPC system to a certain environmental condition. A similar situation was observed in one of my industrial projects in which a kanban system was forced into a non-matching environment driven by the company's corporate strategy to just pull everything. The card allocations had to be adjusted at least once a week or even each day at certain areas because most of the other JIT flow principles could not be established in the production environment.

Slack & Correa (1992) studied different types of flexibility in MRP and JIT systems using range-response curves. There, they found out that the main influence on the response flexibility is the scheduling planning period. Thereby, JIT had in their observation a better performance due to the more frequent updates. However, they also found out that MRP systems have a far greater range flexibility than JIT-based systems.

Plenert (1999) compared MRP and kanban with respect in flexibility and concluded that when flexibility is needed MRP is the unique answer as it can be introduced to a huge range of environments. Only MRP can deal with product variability and customization as well as flexibility in the production process. Another study comparing push and pull principles using simulation was performed by Jodlbauer & Huber (2008). They concluded similar to Plenert (1999) that MRP has its strength in flexible production environments and it also offers the highest stability. However, it might be hard to find the correct parameters. They furthermore pointed out the importance of the PPC systems robustness in flexible environments.

5

CHAPTER

Simulation based Evaluation Study

Essentially, all models are wrong,
but some are useful.
George E. P. Box (1919 - 2013)

Simulation has always played a major role in the analysis of the complex relationships in production and logistics. Especially for the comparison of different PPC strategies, simulation is a key technique to show quantitative advantages of the different methods (Krajewski, et al., 1987; Krishnamurthy, et al., 2004; Jodlbauer & Huber, 2008). Beside standard comparison studies, simulation optimization approaches were also used to find the right PPC strategy for a given production network (Gaury, et al., 2000).

This evaluation study mainly focuses on the evaluation of the impacts due to informatization and the requested flexibility of production. The modelling approach, the aim and focus and the simplifications and assumptions of this evaluation are explained in Chapter 5.1. An in-detail explanation of the used model is given in Chapter 5.2. The experiments using the model are separated in two parts. First, a theoretical scenario considering zero supply variability is investigated to analyze impacts of informatization (Chapter 5.3). Second, the impacts of the supply variability are analyzed in Chapter 5.4.

5.1 Modelling Approach

A model is an abstraction of a real world phenomenon or system. Frantz (1995) suggest the following modeling process for simulation models (see Figure 5.1).

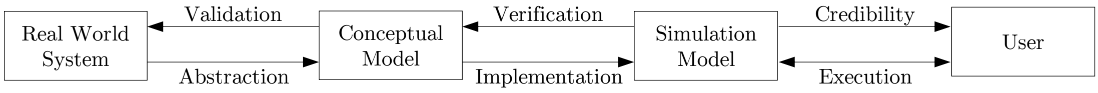

Figure 5.1: Modeling Process[57]

The first step is the development of a conceptual model which is based on the knowledge of the real world system and uses abstractions to reduce the complexity while maintaining the validity. Then the next step is the implementation of the conception model in a computer-executable model. Next, verification is the determination of the accuracy of the simulation model related to the conception model. Finally, the user can execute experiments using the simulation model and make interpretations concerning the real system. (Frantz, 1995)

Modelling techniques are used in PPC for the in-detail analysis of the systems behavior, the run of experiments or so called what-if scenarios and also the validation of planning decisions. Figure 5.2 shows various application fields of simulations in PPC related to their time horizon. On the short term, models are often used to increase the planning accuracy while on the long term, models are used to increase the planning certainty. (März & Krug, 2011)

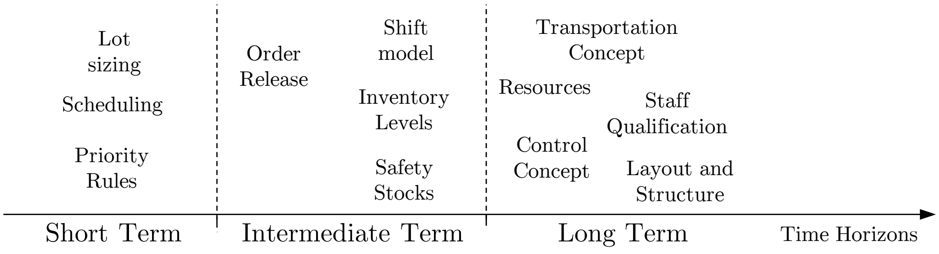

Figure 5.2: Application fields of modeling and simulation techniques in PPC[58]

With the use of modern simulation techniques, the complex behavior of a real world system can be analyzed with high detail but still the famous statement of Box & Draper is true.

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[57] based on Frantz (1995)

[58] based on März & Krug (2011)

> *Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful. (Box & Draper, 1987)*

5.1.1 Modelling Techniques

The needle problem from Buffon[59] (1777) is probably the first example of a simulation experiment. The idea of using independent replications of a simulation to approximate an important physical constant was later on revived by Stanisław Ulam[60] in the design of the hydrogen bomb. By using the ENIAC (see Chapter 3.1.2) he realized that computer-based simulation could be used to estimate the mathematical integrals arising in the design of a workable hydrogen bomb. This idea was then further developed to what is now known as Monte-Carlo simulation. The first discrete event simulator was introduced by K.D. Tocher[61] which was later called General Simulation Program (GSP) using the so called three-phase method for timing control (Goldsman, et al., 2010).

In general, simulations can be classified based on the time dimension:

- Static: representation of the system at a defined time point,
- Dynamic: time dependent representation of the system states, dependent on the certainty of quantities,
- Deterministic: the system has no stochastic components,
- Stochastics: the system states are influenced by stochastic events, and dependent on the nature of the time,
- Continues: system states are changing continuous in time,
- Discrete: system states are changed at discrete points in time (Law & Kelton, 2000).

Discrete Event Simulation

In discrete event simulation (DES), as the name suggests, the system is changed at discrete points in time, so called events. For that different modeling perspectives or *world views* of DES exist which are event scheduling, activity

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[59] Georges-Louis Leclerc, Comte de Buffon (1707 – 1788) was a French naturalist, mathematician, cosmologist, and encyclopedic author. His works influenced the next two generations of naturalists

[60] Stanisław Marcin Ulam (1909 – 1984) was a Polish-American mathematician famous for his participation in the Manhattan Project, developing the Teller–Ulam design for thermonuclear weapons.

[61] Keith Douglas Tocher (1921 – 1981) was a British computer scientist known for his contributions to computer simulation working for the United Steel Companies.

scanning, process interaction. Overstreet & Nance (1986) used the concept of locality to differ amount these three as the following:

> *Event scheduling provides locality of the time: each event routine in a model specification describes related actions that may all occur in a single instant.*
> *Activity scanning provides locality of state: each activity routine in a model specification describes all actions that must occur due to model assuming a particular state (that is, due to a particular condition becoming true).*
> *Process interaction provides locality of object: each process routine in a model specification describes the entire action sequence of a particular model object. (Overstreet & Nance, 1986)*

The further difference between the most used world views event scheduling and activity scanning is in particular the time advancement mechanism. While in event scheduling, the simulation clock advances based on a list which holds several future events, in activity scanning the time is incrementally increased which leads to performance disadvantages but offers the benefit of the continuous visualization of the simulation progress.

Beside that, other techniques such as system dynamics (SD) or agent-based modeling (ABM) are also used, but especially in the discrete part production environment, the technology of DES offers all the capabilities needed. Furthermore, when it comes to performance (simulation time), DES using event scheduling is the only way to go. One concept in which especially this performance is needed is simulation optimization.

Simulation Optimization

Simulation optimization is the concept of finding best input variables from among all possibilities without explicitly evaluating each possibility (Carson & Maria, 1997). Thereby, the simulation model is in the loop with an optimization algorithm executing various experiments (see Figure 5.3). In that way, various optimization strategies can be applied trying to find the best inputs with respect to certain constraints and the time available. Through the use of simulation models to evaluate the input, analytical optimization strategies such as the gradient based search are not possible and often heuristics search approaches are used to find optimal inputs.

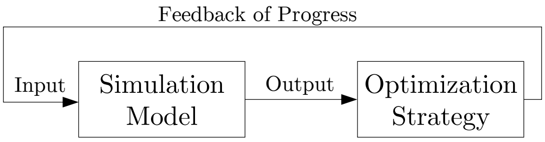

Figure 5.3: Concept of simulation optimization[62]

A search heuristic provides information to orient the search into the direction of the search goal. Thereby, heuristic search strategies typically only find an approximate solution which is close to the real optimal one. Especially in large problem classes such as *NP-hard*[63]*,* this is the only way to find solution because classical methods are too slow and fail to find any exact solution (Edelkamp & Schrödl, 2012). Often applied heuristic search strategies in the production optimization domain are genetic algorithms (GA), which are based on the biological evolution, simulated annealing (SA), which is based on the physical annealing process of an alloy, or simple greedy algorithms (Carson & Maria, 1997).

5.1.2 Aim and Focus

As in the previous chapters discussed, the main challenges of manufacturing companies are nowadays more individual customer demands and the increasing dynamics of the market. Furthermore, the advancements in ICT leads to new possibilities in the field of PPC. The main goal of this thesis is to evaluate different PPC concepts regarding these challenges and prospects using simulation techniques (see Figure 5.4).

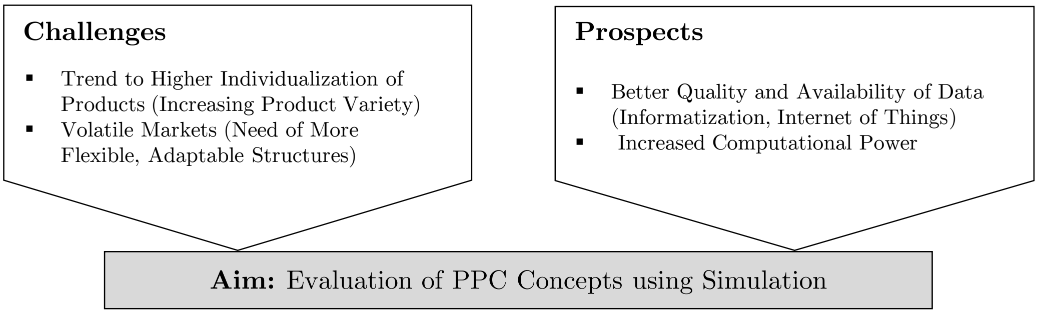

Figure 5.4: Motivations for the evaluation

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[62] based on Carson & Maria (1997)

[63] NP-hard (Non-deterministic Polynomial-time hard) is in computational complexity theory a class of problems that cannot be solved in polynomial time. Several production related optimization problems such as the job-shop problem are of this problem class (Edelkamp & Schrödl, 2012).

Evaluation studies have always played a major role in the comparison of different PPC paradigms. The most prominent and earliest one was carried out in the evaluation of push and pull manufacturing principles (Krajewski, et al., 1987) coming to the findings discussed in Chapter 4.5.2. Also in the performance evaluation of agent-based manufacturing paradigms, discrete production simulation is the core tool for the study of these systems. Through the revitalization of these paradigms in the research version Industry 4.0, several simulation models were built to analyze CPS. In these studies, mainly job-shop[64] problems are analyzed in which the main goal is to optimally route the individual jobs through the available resources. Thereby, the to-be-processed jobs are given through a prior MRP planning procedure and have to be pushed optimally through a given network of machines by fulfilling several process and product related constrains. For example, this kind of problem is typically for the wafer production in electronic industry in which the jobs have to be passed several times through certain processes with different machines available to perform these processes (Mönch, et al., 2013). A different process structure is the flow-shop with disconnected flow lines which can be especially found in the automotive supply industry of heavy items such as gearboxes, engines, axles and so on. As already discussed in Chapter 1 the main focus of this thesis is such a discrete part production using disconnected flow lines. Thereby, the routing between the individual workstations in line is fixed using various types of conveyor systems. This stands in contrast to the job-shop process type, where the routing between the workstations is variable depending on the individual requirements of the processed parts (Groover, 2007). The difference of these two types can be seen in Figure 5.5.

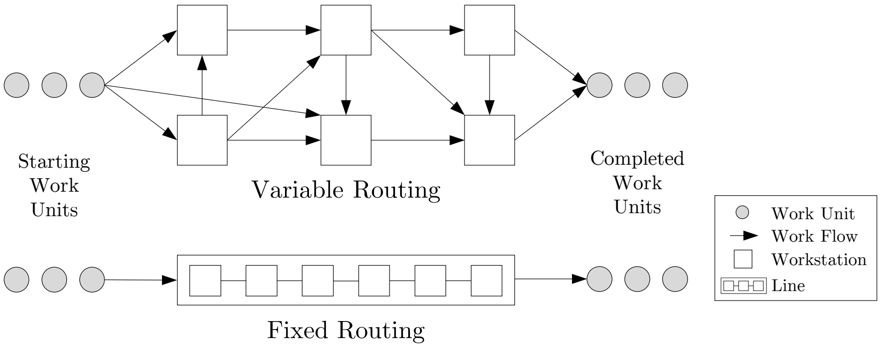

Figure 5.5: Different types of routing in manufacturing systems[65]

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[64] In OR different classes of scheduling problems are defined. In job-shop scheduling several jobs of varying sizes need to be scheduled on identical machines, while trying to minimize the makespan. Flow-shop scheduling is a special case of job-shop scheduling where there is strict order of all operations to be performed on all jobs (Graves, et al., 2002).

[65] adapted from Groover (2007)

While in an agent-based job-shop environment, the individual jobs ask their manufacturing environment who can process the next task of their work plans, in a flow-shop environment the PPC challenge is an essential different one. In a flow-shop, the main duty of each line is to specify the quantity and timing of the production jobs of the individual types to fulfill the needs of the downstream customers (either other production lines or the final assembly) while keeping the overall WIP at a low level. Therefore, also different approaches using CPS are needed for this type of production.

The goal of the evaluation study is to analyze various PPC methods regarding their flexibility to respond to external changes and the impacts of the informatization in manufacturing on these methods.

Based on the different types of flexibility defined in Chapter 2.5.1, the product and the volume flexibility of Sethi & Sethi (1990) and respectively the mix and volume flexibility of Koste & Malhotra (1999) were identified as the major sources of flexibility that are associated to production planning activities. The volume flexibility is not considered in this evaluation study as it is assumed that the production is overall leveled and volume increases or decreases have to be affected in the aggregate planning level. This assumption is particularly proper in automotive production because in this industry field, the capacities are leveled by contracts between the individual manufacturing sides over several years. Volume increases or decreases are only possible by the adjustment of the number of shifts which is done in the aggregate planning. However, the product or mix flexibility is a major concern in this manufacturing environment. This flexibility type is modeled in this evaluation study by two dimensions, the range of parts (products) that can be produced and the demand mix which describes fluctuations in the demand of the different products over the time.

In the automotive serial production of mechanical heavy items, only a moderate number of different products are typically produced. The impacts of data quality through informatization will therefore mainly affect transactional data while master data is currently a manageable challenge through the moderate number of products. The impacts of informatization are modeled with different availabilities and qualities (deviations) of the transactional data needed for planning. This includes inventory and demand forecast data.

Furthermore, the investigation is taking variability and lead time effects of the line into consideration. Table 5.1 gives an overview of the different evaluation dimensions analyzed in this study.

	Characteristic	
Type	Internal (Supply)	External (Demand)
Flexibility & Variability	Setup time Supply variability (MTTR)	Part range Demand mix
Data Quality & Availability	Inventory deviation Planning cycle	Forecast changes Forecast update frequency
Others	Lead time	

Table 5.1: Evaluation dimensions of the study

The impact of the flexibility and variability is analyzed on the external side by the two above described dimensions' part range and demand mix and on the supply side by the setup time and different supply variability settings due to machine breakdowns. The aspects of informatization are analyzed on the internal side in the dimension quality by different deviations in the inventory level and in the dimension availability in various frequencies of the data availability resulting in different planning cycles. On the demand side, the impact of informatization is covered by different amounts of changes in the forecast as well as different update frequencies of the forecast.

5.1.3 Simplifications and Assumptions

To analyze different PPC methods regarding the mentioned challenges and prospects, several simplifications and assumptions have to be considered in the simulation based evaluation study. Especially for the manufacturing model used in the simulation, numerous limitations have to be considered because nearly every production system has a different setting and even within one production line various configurations are possible that cannot be considered in a representative general model. The scope of the evaluation study is a single supplying flow line and its associated customer (see Figure 5.6). This assumption includes that no network effects between the individual lines of a production network are analyzed. The manufacturing model of the supplier uses a conveyor model which is specified in more detail in Chapter 5.2.3.

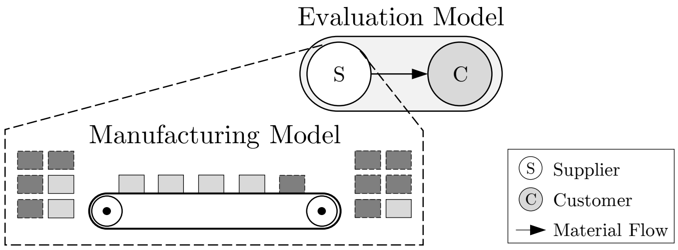

Figure 5.6: Scope of the evaluation study

This general relationship between a suppling line and a customer can be widely found in any production network of the automotive supply industry. Figure 5.7 gives an example of two applications of this evaluation model in a multistage and multicomponent production network. In the Application 1, the customer is another production line (M5) while in the Application 2 the customer is the final assembly (A) of this production network.

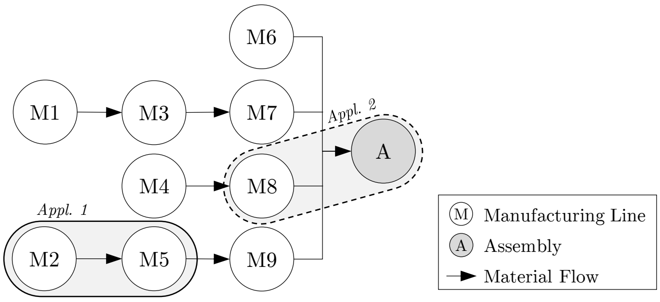

Figure 5.7: Two examples of applications of the evaluation model in a multistage and multicomponent production network

In the generic evaluation model, a simple line with one static bottleneck is considered. Any complexity issues inside the line due to its topology are out of focus in this model. The evaluation model, furthermore, only considers one single entry and one single output of the line. Another simplification is the assumed infinite supply of parts to the manufacturing line and the assumption of a yield of 100% (no quality defects). The times (e.g. processing time, lead time,...) used in the evaluation model are based on collected data from projects and represent standard scenarios of industry. Independent on the selected times of this evaluation study, the result of these simulations are also valid for other settings if the proposition of the values is equal. For simplicity reasons it is assumed that the cycle times, lead times and setup times used in the manufacturing model are deterministic. Only the breakdowns, the customer manner and the data defects have a stochastic behavior. Moreover, the cycle times and setup times are independent of the produced part type and the transportation lot size to the customer is one. Finally, beside the consideration of the data quality of inventory and demand, it is assumed that the master data used in production planning is of 100% quality and availability.

5.2 Model Design

The model used in this evaluation study is built on data and insights of evaluation studies in literature (Krajewski, et al., 1987; Krishnamurthy, et al., 2004; Jodlbauer & Huber, 2008) and from industrial projects in the gearbox and engine production. The evaluation model is implemented in Plant Simulation 9 using an ActiveX interface to execute external planning macros. The general structure and the used customer and manufacturing model is explained in this chapter.

5.2.1 General Structure

The general structure of the evaluation model consists of three main parts (see Figure 5.8). First of all, it consists of a manufacturing model of a flow-shop production with disconnected flow lines. Second, the model contains a customer model based on the logistic principles of automotive supply industry. These two components are implemented in a DES software package. In addition, the evaluation model contains various PPC-methods which are either linked via programming interfaces to the DES or are directly implemented in the simulation program.

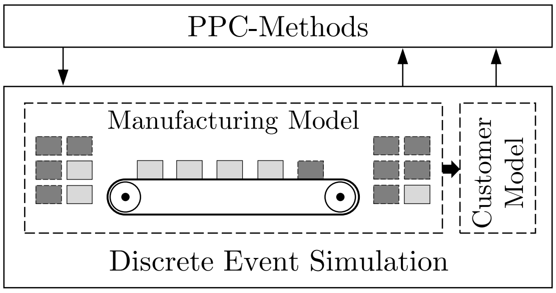

Figure 5.8: General structure of the evaluation model

Using this model, various standard parameter scenarios are analyzed over a simulation time of several days depending on the problem. This simulation time includes a warm-up period and an evaluation period. It is assumed that the production is running during this period without any planned downtimes. As the model is using various probability distributions, for every scenario numerous simulation runs with different seed values for the random number generator are executed. More detailed data on the evaluation period and the number of seeds can be found in the data tables of the appendix. Details on the statistical analysis of the simulation results are provided in the beginning of Chapter 5.3 and Chapter 5.4.

5.2.2 Customer Model

The single source of demand in the simulation model is the customer which has a rigid pacing with a takt time of 60 seconds. The demand of this customer is leveled and is in lot of 60 pieces, which means considering the takt time that lot changes may occur every hour.

One main aspect in the evaluation study is the range of parts. In the evaluation three different range of parts scenarios are evaluated:

- 2 parts (2P): A, B
- 4 parts (4P): A, B, C, D
- 8 parts (8P): A, B, C, D, E, F, G, H

The second main aspect is the change of the demand mix over time. Thereby two main scenarios are analyzed in the evaluation model. The static mix (SM) demand scenario represent an equal, stationary part distribution over the simulation time. In the dynamic mix (DM) scenario the demand mix of a parts fluctuates within ±25% over the simulation time (see Figure 5.9).

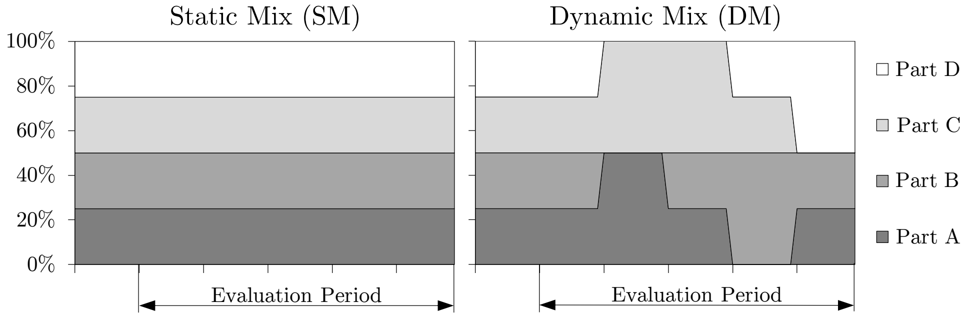

Figure 5.9: Different demand mixes

The demand is generated by the customer model using a seeded random number generator and a roulette algorithm based on the given demand mix. Figure 5.10 shows an example with a sampled demand using this approach.

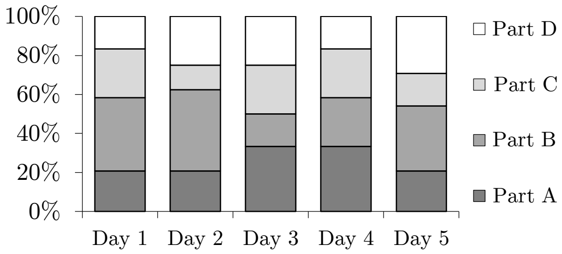

Figure 5.10: Example of a sampled demand (4P, SM)

The customer is backordering the demand if the requested parts cannot be supplied. The amount of pieces backordered is used to calculate the service level, which is one of the main KPIs in that evaluation model.

$$Service\ Level = 1 - \frac{\sum Backordered}{\sum Demand} \tag{5.1}$$

As it is common in the automotive industry the demand is shared between original equipment manufacturer (OEM) and suppliers using electronic data interfaces (EDI) with standards of the *Verband der Automobilindustrie* (VDA), the *Organization for Data Exchange by Tele Transmission in Europe* (ODETTE) or the *Electronic Data Interchange for Administration, Commerce and Transportation* (EDIFACT). Especially the German based OEM are using the VDA standard with the delivery instruction VDA 4905 which gives an aggregated forecast, and the call-off instruction VDA 4915, which contains detailed requested goods delivery information in type, time and quantity. Also in the customer model shared forecast data are used which is updated in the beginning of each day. The horizon of this detailed forecast are ten workdays. During this forecast horizon changes in the demand are allowed to certain percentage for the individual days based on the model shown in Figure 5.11.

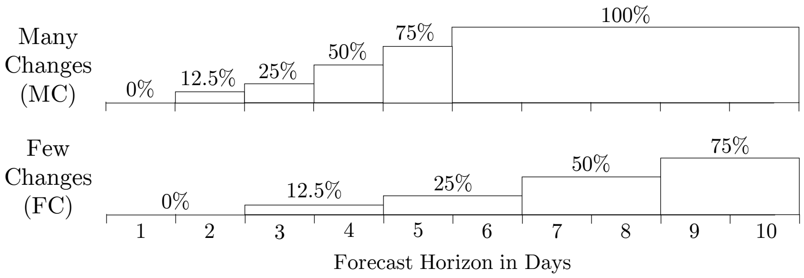

Figure 5.11: Demand changes in the forecast

Thereby three different scenarios are considered: many changes (MC), few changes (FC) and no changes (NC). The MC and FC scenarios have a frozen period in which no changes are allowed while in the NC scenario no changes occur in the demand during the whole evaluation period. In the MC scenario, the frozen period is one day while in the FC scenario no changes are allowed during the first two days. For the other days in the forecast horizon, changes in the demand happen to the defined percentages. The 12.5% changes of the MC scenario at the second day mean that of the 24 assembly lots, three lots change to the previous forecast. These changes are based on the random roulette algorithm using the same demand mix.

5.2.3 Manufacturing Model

The manufacturing model is based on the conveyor model by Hopp & Spearman (2008) which fulfills the requirements of disconnected flow lines. In the conveyor model a manufacturing line is simplified by a conveyor with a certain production rate (t_{Takt}) and lead time (t_{Lead}). In addition, the simple conveyor model is extended with setups (t_{Setup}) and breakdowns (Availability, MTTR) in the simulation. Figure 5.12 shows the basic idea of the conveyor model.

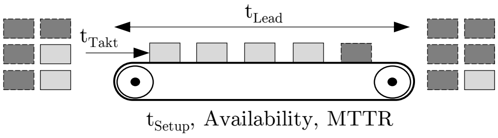

Figure 5.12: Conveyor model[66]

In the DES software, this model is implemented using a simple single station which can process one part (SingleProc in Plant Simulation) with t_{Takt}, t_{Setup}, Availability, MTTR in combination with a transportation conveyor (Line in Plant Simulation) with a defined length and velocity to model t_{Lead}.

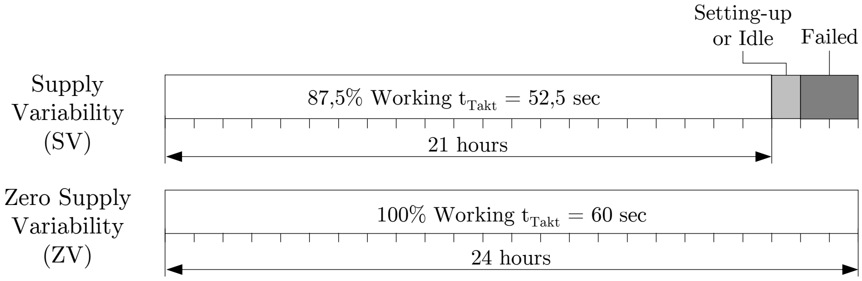

Figure 5.13: Variability of the manufacturing line

In the evaluation study, two main variability scenarios with several parameter settings are used (see Figure 5.13). In the zero variability (ZV) scenario, the setup time is zero and no breakdowns occur. This theoretical scenario with 100% availability of the manufacturing line is used to evaluate various influences with no consideration of the manufacturing variability. The supply variability (SV) scenario represents common manufacturing settings in the field of automotive supply industry considering different setup times and breakdowns behavior (see Table 5.2). In this scenario, the t_{Takt} of the manufacturing line is set to 52,5 seconds to ensure that the daily demand of 1440 pieces of the customer can be manufactured in 21 hours. The remaining three hours are used for breakdowns

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[66] adapted from Hopp & Spearman (2008)

(on average two hours) and for setting-up or idle time to ensure that the line can recover after a breakdown.

	Supply Variability Scenarios						
	ZV (zero)	SV					
		MTTR1			MTTR4		
Parameter		ST0.5	ST1	ST2	ST0,5	ST1	ST2
t_{Takt}	60 sec	52,5 sec	52,5 sec	52,5 sec	52,5 sec	52,5 sec	52,5 sec
t_{Setup}	0 min	30 min	60 min	120 min	30 min	60 min	120 min
Availability	100%	87,5%	87,5%	87,5%	87,5%	87,5%	87,5%
Failed	0%	8,33%	8,33%	8,33%	8,33%	8,33%	8,33%
MTTR	0 min	60 min	60 min	60 min	240 min	240 min	240 min

Table 5.2: Parameter of the different supply variability scenarios

In the supply variability (SV) scenarios different mean times to repair (MTTR) of the manufacturing line are modeled using the Erlang-distribution[67]. For each MTTR scenario three different setup time scenarios are used. These setup times vary between 30 (ST0.5) and 120 (ST2) minutes and are modeled as deterministic times. The difference between the resulting repair times of these two average repair time scenarios MTTR1 and MTTR4 is shown in a histogram in Figure 5.14. Thereby it can be seen that the longest repair time in the MTTR1 scenario is around four hours while in the MTTR4 scenario the repair time can rise to up to even 12 hours.

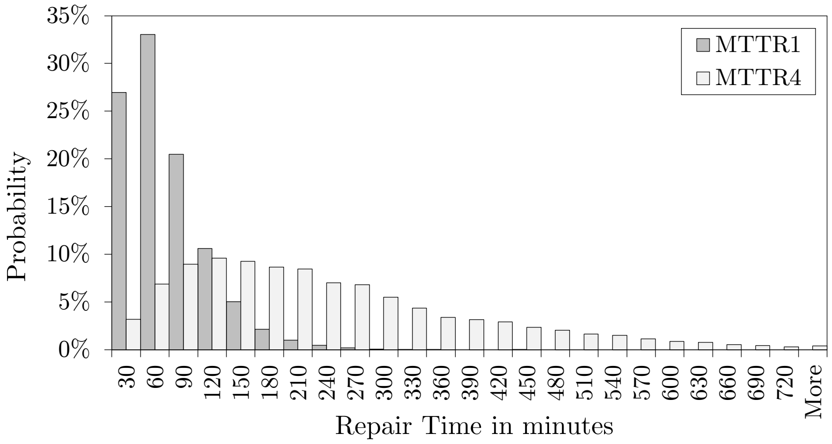

Figure 5.14: Repair time histogram of the low/high variability scenarios[68]

Another parameter inside the manufacturing model is t_{Lead} which has combined with the forecasting accuracy, a major influence on the reliability of the planned

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[67] The Erlang-distribution is the sum of two independent exponentially distributed random numbers with the same parameter β. The used Erlang-distribution also has the property $\sigma = \mu/\sqrt{2}$ (Plant Simulation, 2008).

[68] based on data from a simulation study over 10.000 days.

production. Figure 5.15 shows this influence using an example. Thereby the production at day 1 16:00 is determined by the demand at day 2 04:00 due to the t_{Lead} of 12:00. As in this example the demand of day 2 is outside the frozen period and 12.5% changes are allowed, the planned production might be wrong.

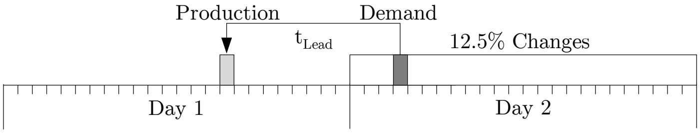

Figure 5.15: Example of the influence of the lead time

In the evaluation study two standard scenarios for t_{Lead}, often found in the flow-shop manufacturing environment, are used: 4 hours (LT4) and 12 hours (LT12).

Beside the lines implemented with the conveyor model, the manufacturing model consists of a supermarket between the line and the customer. In this supermarket, the individual parts are stored with no upper limit in storage capacity.

Other parameters in the manufacturing model are the data quality and availability which have a major influence on the push type PPC methods. On the supply side, the data requested for planning are the stock levels of the individual parts. To model different data qualities, the stock levels from the simulation are randomized using a normal distribution with the actual stock level as expected value $\mu = actual\,stock$ and the error as standard deviation $\sigma = actual\,stock * error\,factor$. The data availability is modeled by having the stock level only available at certain time intervals (see Table 5.3). These time intervals have a major impact on the possible planning cycle (PC) of the push type PPC methods.

Property	Parameter	Settings		
Data Quality	Error Factor	High Quality (HQ) - 0%	Medium Quality (MQ) - 10%	Poor Quality (PQ) - 25%
Data Availability	Time Intervals	real time (PC1)	every 24h (PC24)	every 120h (PC120)

Table 5.3: Manufacturing data quality and availability settings

5.2.4 PPC-Methods

The common PPC-methods applied in the field of automotive supply flow-shops use the basis push and pull type principles discussed in Chapter 4.5.2. Hence, in this evaluation study, these principles with their common representatives kanban and MRP are implemented. Within the MRP-based methods, the two basic modeling approaches big bucket and small bucket time models are used. In this chapter the implemented PPC-methods kanban, small bucket MRP and big bucket MRP are explained in-detail.

Kanban Configuration

The implemented kanban system is a single card kanban system such as shown in Figure 4.12 with a defined container size and a certain amount of kanban cards for each part. As in the two product mix cases (SM, DM), the demand over the evaluation period is uniform distributed, the amount of kanban cards for the different parts is equal.

The kanban system is directly implemented in the DES by attaching to every last part of a container a signal which indicates by removing this part from the supermarket a production order. This order signal is passed without delay to the kanban board in front of the line in which the individual production orders are executed in their sequence of request (FIFO principle).

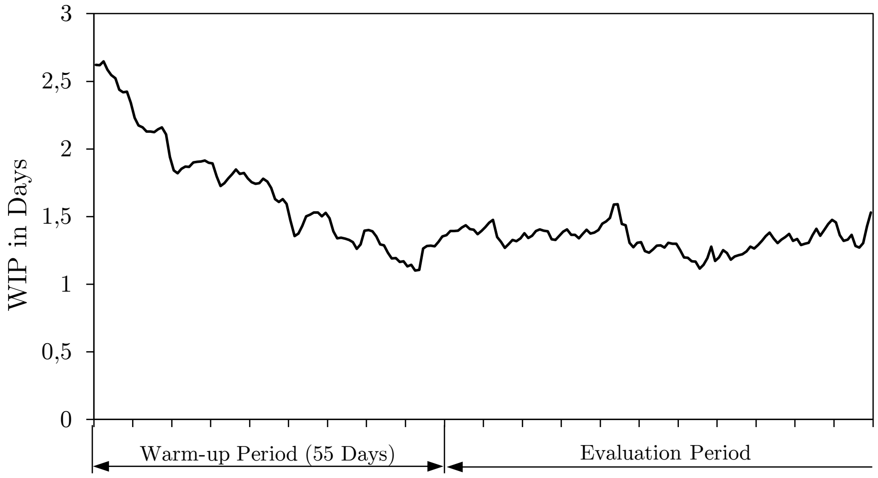

Figure 5.16: Length of the warm-up period using a kanban system[69]

In the initialization of the simulation, it is assumed that the supermarket is filled up to the limit with all possible containers and the kanban board is empty. In case of a too small container sizes the kanban system will require more setups

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[69] simulation settings: 4P, SM, LT4, ST0.5, MTTR1, 2 kanban cards for each part, 480# container size

than capacity for setting-up is reserved (see Figure 5.13). This then leads to a drop in the total stock level over the time until, after a certain warm-up period, a steady state is reached. Depending on the container size, this warm-up can be significantly long and has to be considered in the evaluation of the results (see Figure 5.16).

MRP Configuration

The implemented MRP-based algorithms are coupled via an interface to the DES. Thereby on the one hand the demand forecast, the current inventories of all parts and in case of the small bucket MRP algorithm the setted-up part ID or in the big bucket algorithm the current production plan is readable from the simulation. On the other hand, the production plan is written from the MRP-based algorithm to the DES (see Figure 5.17).

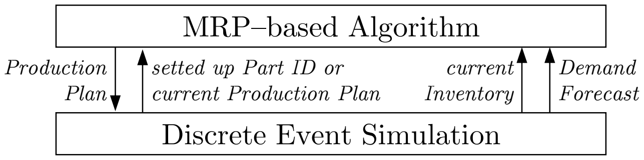

Figure 5.17: Exchanged data between the DES and the MRP-based Algorithm

In the MRP-based algorithms, the modeling approach small and big time bucket is used.

Small Bucket MRP

The implemented small bucket MRP system uses a time bucket size of one hour as the assembly is also working on an hourly basis (compare Chapter 5.2.2) and the manufacturing lead time is a multiple of one hour. Consequentially, the smallest manufacturing lot size is in the ZV case 60 pieces and in the SV cases 69 pieces.

The applied small bucket MRP model uses a greedy heuristic[70] approach which keeps the inventory ranges of all parts within defined boarders ($\text{Range}_{\text{MIN}}$, $\text{Range}_{\text{MAX}}$) and plans for every part to be produced at minimum for a certain period of time steps ($\text{Lotsize}_{\text{MIN}}$). Figure 5.18 shows an example using the small bucket MRP approach with four parts over a period of five days.

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[70] is following the problem solving approach of selecting at each step the locally optimal choice with the hope of finding a global optimum

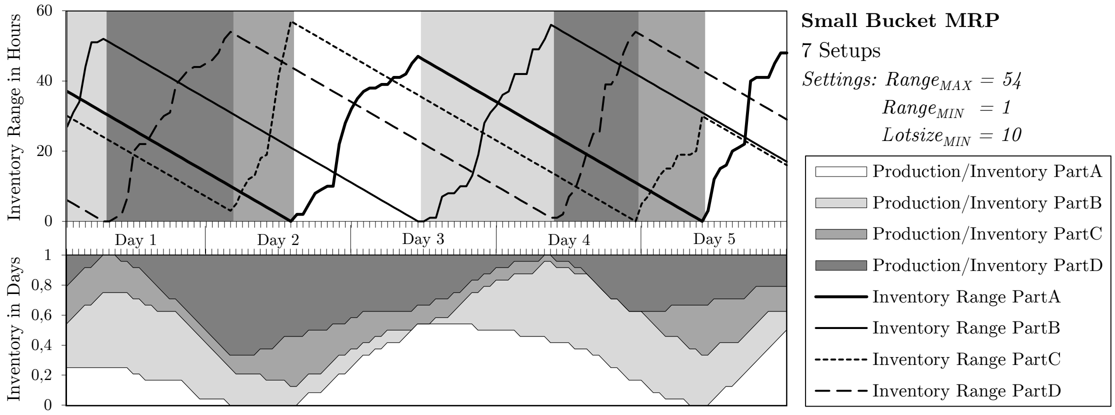

Figure 5.18: Example of the small bucket MRP algorithm[71]

The core of the small bucket MRP algorithm is shown in the flowchart of Figure 5.19. This algorithm calculates for *p* parts over *t* time steps with a given initial inventory and a given demand forecast a feasible production plan. The parameter minimum/maximum inventory range ($Range_{MIN}$, $Range_{MAX}$), initial minimum lot size ($Lotsize_{MIN}$) and the maximum amount of time steps (t_{END}) are handed over to this algorithm.

In the first step (1) the initial inventory for all parts *p* is read and stored in the variable *Stock(p,t)* at position *t=0.* Furthermore, the demand for all parts *p* and time steps *t* is read and stored in *Demand(p,t).* The manufacturing lead time is also read and stored in the variable t_{LT}. In the last action of (1), the initial stock *Stock(p,0)* of all parts *p* is decreased by the demand of the first time steps *t* smaller that $t_{LT}+1$ because these pieces already have to be in production. In the next step (2), the algorithm is initializing the time step index *t* to one, setting the setup counter $counter_{SETUP}$ to zero and setting the production amounts *Production(p,t)* for all parts *p* and time steps *t* to zero. Moreover, the ID of the current setted-up part is stored in the variable. In step (3), a loop of the following steps (4) to (10) is performed as long as the time step index *t* is smaller than the maximum amount of time steps t_{END}. The steps (4) to (6) contain the dynamic production adding part of the algorithm. In this part, the algorithm is adding time step for time step production of the selected part p_{SEL} (6) until either the inventory range *StockRange(p)* at time step *t* of any part *p* falls below the minimum allowed inventory range $Range_{MIN}$ or the maximum inventory range $Range_{MAX}$ of part p_{SEL} is reached (5). If one of these conditions is fulfilled, the algorithm moves on to the lot production adding part of step (7) to (10). In this part of the code (7), the algorithm searches for a new part p_{SEL} with the lowest inventory range $StockRange(p_{SEL})$ and increases the setup counter $counter_{SETUP}$.

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[71] see input data in Appendix A1

In a loop (8) for *tt* time steps smaller than the minimum lot size $Lotsize_{MIN}$ production of the selected part p_{SEL} is added and the new stock is calculated (9). If the stock of any part *p* falls below zero (10), the code stops, decreases the lot size $Lotsize_{MIN}$ by one and starts over at (2). When the loop (8) is finished, the time step index *t* gets increased by *tt* and if the maximum amount of time steps t_{END} is not reached (3), the algorithm starts over with the dynamic production adding (4).

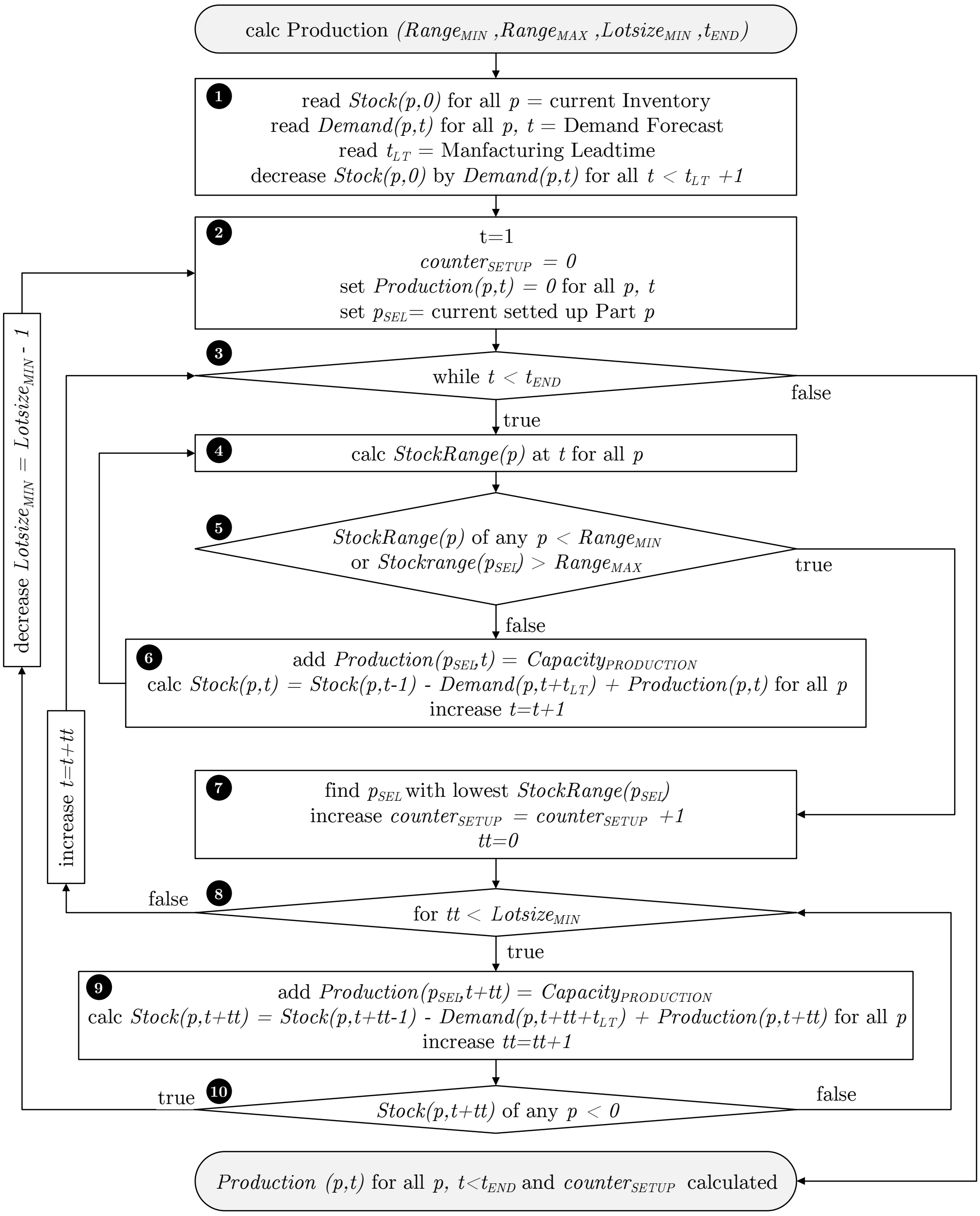

Figure 5.19: Flowchart of the small bucket MRP core algorithm

The amount of setups required depends on the upper limit for the inventory range $Range_{MAX}$ and the given total inventory level (see Figure 5.20).

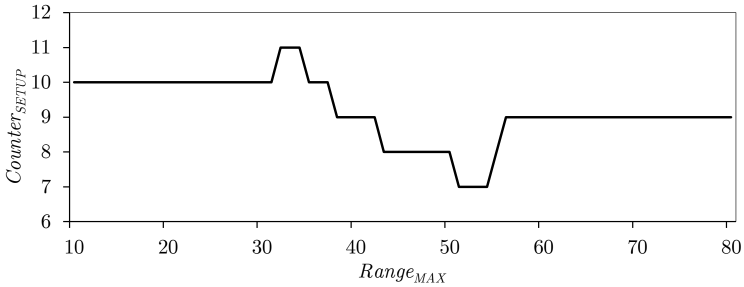

Figure 5.20: Relationship of maximum inventory range and setup counter[72]

To find a setup optimal setting for $Range_{MAX}$, the search algorithm shown in Figure 5.21 is used. In this algorithm the $Range_{MAX}$ parameter is increase stepwise between a lower and an upper limit. First of all, the initial maximum range $Range_{MAX}$ is set to the lower limit $Range_{LOWERLIMIT}$ and the variable $optimum_{SETUP}$ is set to a very high number (1). Within a for loop (2), the small bucket MRP core algorithm is called (3) and the amount of setups needed is compared with the variable $optimum_{SETUP}$ (4). If the new solution is better than the already found one, the production plan *Production(p,t)* gets stored as *OptProduction(p,t)* and the variable $optimum_{SETUP}$ is updated (5). The $Range_{MAX}$ is then increased by a step $Range_{STEP}$ (6) and the loop is executed until the upper limit $Range_{UPPERLIMIT}$ is reached.

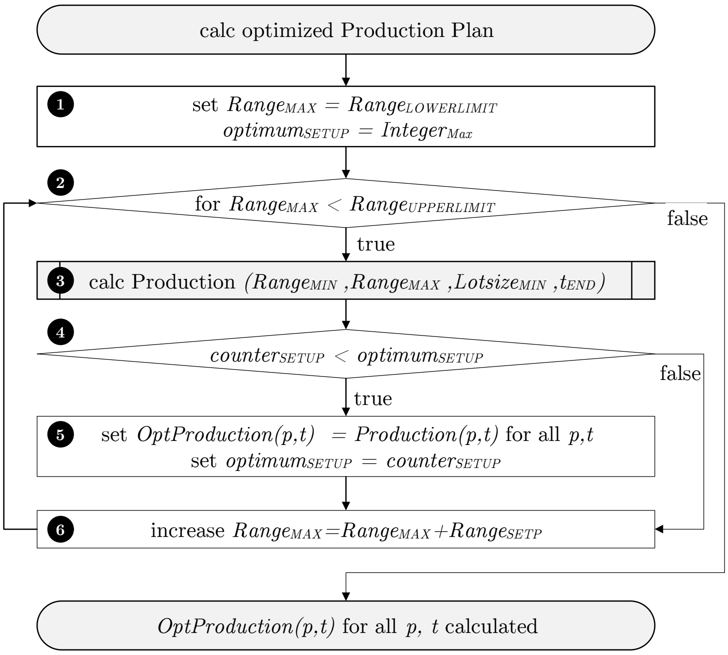

Figure 5.21: Flowchart of the maximum range optimization of the small bucket MRP algorithm

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[72] same input data of Appendix A1 used as in the example of Figure 5.18

The close to optimality of the small bucket MRP algorithm is proven in a comparison with an LP model using the Gurobi solver. In this model, the demand for all parts i and time period t is given in a binary form. Using the following notation:

$P_{i,t}$ = production of part i to be scheduled at time period t (binary)
$\alpha_{i,t}$ = setup decision of part i at time period t (binary)
$D_{i,t}$ = demand of part i at time period t (binary)
$S_{i,t}$ = inventory of part i on hand at the end of time period t (units)

the LP model solves the objective of minimizing the sum of the required setups by variation of the variables $\alpha_{i,t}$ and $P_{i,t}$.

$$min \sum_i \sum_t \alpha_{i,t} \tag{5.2}$$

with subject to the following constraints:

$$\begin{aligned}
M(1-P_{i,t})+\alpha_{i,t} &\geq \sum_{j\in I\setminus\{i\}} P_{j,t+1} && for\ all\ i,t\\
S_{i,t-1}+P_{i,t}-D_{i,t} &= S_{i,t} && for\ all\ i,t\\
S_{i,t} &\geq 0 && for\ all\ i,t\\
\sum_i P_{i,t} &= 1 && for\ all\ t\\
P_{i,t} &= binary && for\ all\ i,t\\
\alpha_{i,t} &= binary && for\ all\ t
\end{aligned}$$

Due to the complexity of the LP model, a comparison with the small bucket MRP heuristic is only possible for a problem with four parts over a period of four days with a maximum of 96 time steps. Figure 5.22 shows this comparison using the same demand data as in Figure 5.18 and varying the WIP between one hour and 24 hours. Thereby, it can be seen that the heuristic finds optimal or very close to the optimal solutions, especially at higher WIP-levels. For this problem size, the small bucket heuristic needs just a few milliseconds, while the solver runs around three minutes on a state of the art personal computer.

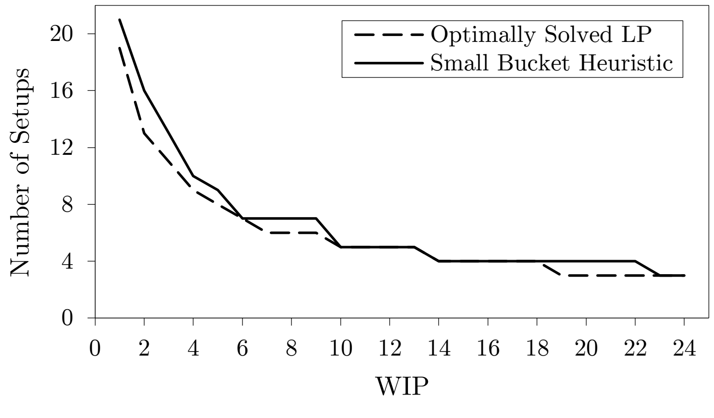

Figure 5.22: Comparison between optimal and heuristic solution

Big Bucket MRP

The implemented big bucket MRP system uses a time bucket size of one day.

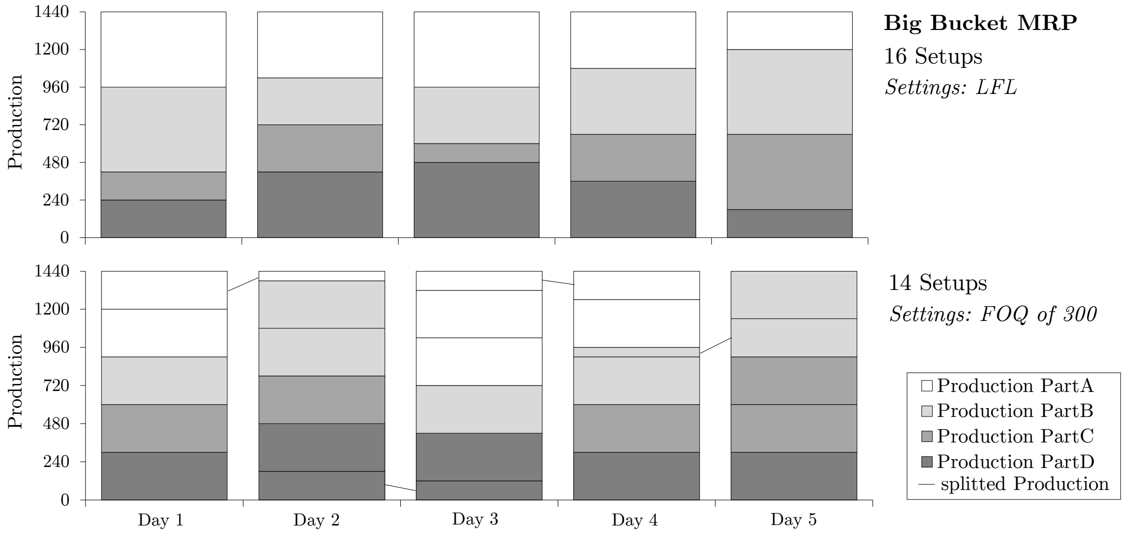

Figure 5.23: Example of the big bucket MRP algorithm[73]

Therefore, it is assumed in this planning model that the lead time is also one day so that all pieces required for the actual day have to be produced at the previous day. Consequentially, this drives the amount of WIP and it is not possible to operate this system below an inventory range of one day.

Figure 5.23 shows an example with the same input data of Figure 5.18 using the big bucket MRP approach with four parts over a period of five days. Thereby, the standard lot-sizing policies LFL and FOQ are used. In comparison with the small bucket solution of Figure 5.18, a clear disadvantage in the amount of setups required can be seen.

In the first step (1), the initial inventory for all parts *p* is read and stored in the variable *Stock(p,T)* at position T=0. Furthermore, the demand for all parts *p* and time steps *t* is read and stored in *Demand(p,t).* The big letter *T* is the index for the time steps in the big bucket size while the small letter *t* indicates the small bucket time steps which are used in the simulation to generate the demand. The initial stock *Stock(p,0)* of all parts *p* is decreased by the demand of the first time steps *t* smaller than the bucket size $t_{BUCKETSIZE}$ (for a bucket size of one day $t_{BUCKETSIZE} = 24$). Then the demand *Demand(p,t)* is converted for all small time steps bigger than the bucket size $t_{BUCKETSIZE}$ into the big time step format *Demand(p,T)*. In the last action of (1), the sum of the production amounts $Production_{SUM}$ and the production plan index *i* are set to zero. In the next steps

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[73] see input data in Appendix A1

(2) and (3), the algorithm reads the current production plan for the first day. Therefore in step (2), the part p_{SEL} of the current production plan at position i is read. The stock $Stock(p_{SEL},0)$ and the sum of the production amounts $Production_{SUM}$ is then increased by the planned amount of the production plan. This step is executed while the sum of the production amounts $Production_{SUM}$ is smaller than the production capacity $Production_{CAPACITY}$ of one time bucket (3).

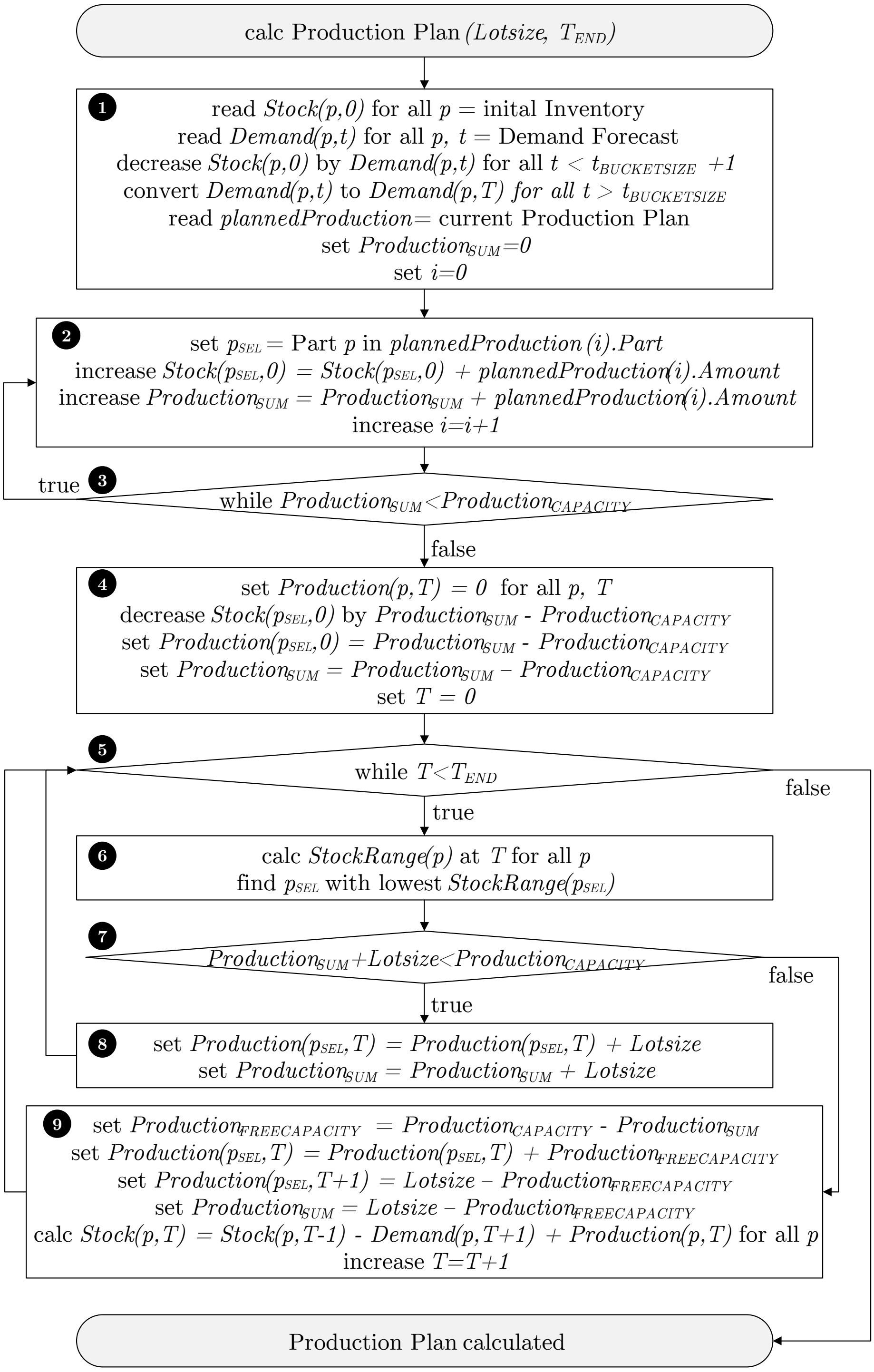

Figure 5.24: Flowchart of the big bucket MRP algorithm

Next in step (4), the production amounts *Production(p,T)* for all parts p and time steps T are set to zero. The stock of the part p_{SEL} at position T=0 is then decreased by the over production calculated by the capacity minus the sum of the production amounts and the production of the part p_{SEL} at position T=0. The sum of the production amounts is also set to this value. Last in step (4), the time step index T is set to zero. In step (5), a loop of the following steps (6) to (9) is performed in which lots in the defined size *Lotsize* are added to the individual time steps. Therefore in step (6), the algorithm searches for a part p_{SEL} with the lowest inventory range StockRange(p_{SEL}). In case that the sum of the production amounts plus the lot size is smaller than the production capacity, the lot can be directly added to the actual time step and the sum of the production amounts is increased by the lot size (8). Otherwise (9) the free capacity is calculated and the to be added lot is split by this amount between the actual time step T and the next time step *T+1.* Thereby, the new stock is calculated and the time step index T is increased by one (9).

This algorithm has obviously the limitation that the lot size cannot be bigger than the capacity of two big bucket time steps. Furthermore, it is assumed that the lead time is not longer than 24 hours.

5.3 Evaluation of Informatization and Demand Flexibility

The aim of the first evaluation study is to evaluate the performance of the three analyzed PPC-methods regarding their ability to handle a certain demand variability and their robustness against data errors. Therefore, simulation settings are used in which only these influences are taken into account. The performance measure required setups at a certain WIP level is used to analyze how good the PPC-method can follow the requested demand.

5.3.1 Settings

In this evaluation, the ability of a single flow line to respond to a given demand under a certain quality and availability of data is of interest. It is assumed that this line has no internal variability (ZV), so one can only evaluate the above mentioned impacts. Table 5.4 shows the simulation settings of this scenario. Thereby, the main source of variability arises from the part range (2P, 4P, 8P) as well as the various demand mixes (SM, DM). The data quality is modeled on the supply side with various errors in the inventory levels used in planning (HQ, MQ, PQ) and on the demand side with various forecast changes (NC, FC, MC). Furthermore, the internal data availability (PC1, PC24, PC120) is taken into consideration as well as two different lead time scenarios (LT4, LT12).

	Characteristic	
Type	Internal (Supply)	External (Demand)
Flexibility & Variability	ZV	2P, 4P, 8P SM, DM
Data Quality & Availability	HQ, MQ, PQ PC1, PC24, PC120	NC, FC, MC update every 24h
Others	LT4, LT12	

Table 5.4: Simulation settings of the evaluation of informatization and demand flexibility

To make a comparison between the two parameters WIP and required setups possible, the third considered performance indicator service level must be on the same level. Therefore, this comparison is done at the service level of 100% requiring an additional parameter optimization of the different PPC-methods. Figure 5.25 shows the used structure of the evaluation model in this scenario. Depending on the method, different parameters are optimized to achieve the desired service level of 100%.

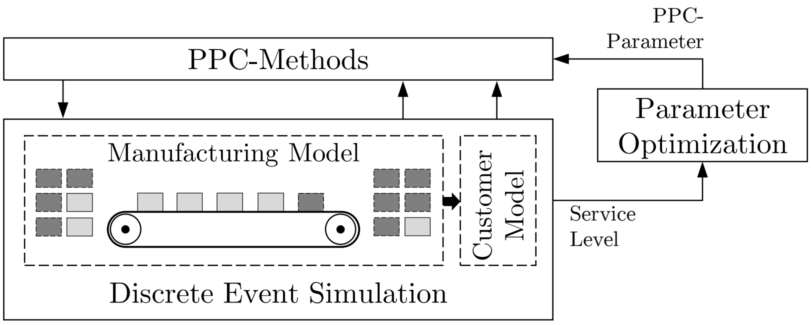

Figure 5.25: Parameter optimization for 100% service level

Kanban

For the kanban method, the main parameter for a given container size is the amount of containers used for every part in the system. As the part distribution in the SM as well as the DM is the same for every part over the evaluation period the same amount of containers is used for all parts. In the parameter optimization, the amount of containers used for a certain container size is varied in steps of one and the service level is analyzed. Thereby, it turned out that for all the different demand scenarios a two container kanban system fits best.

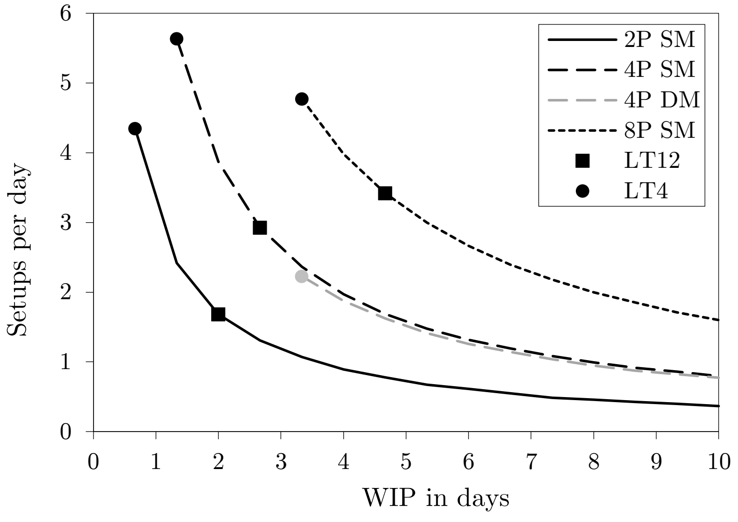

Figure 5.26: Kanban system in the ZV scenario[74]

In the kanban system the range of parts has a highest influence on the required setups while the demand mix only show a minor influence.

Figure 5.26 show the results of the kanban method. As the kanban method does not use any centralized information, these results are independent on the data quality and availability. It can be seen that the part range has a high influence in the amount of setups required for a certain WIP level. The lead time has an influence of the WIP level at which the two container kanban system can operate

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[74] based on data found in Appendix A2.1

at 100% service level. Clearly it can be seen that with longer lead times (LT12) a higher WIP level for 100% service level is needed. However, the simulations showed that the relationship between WIP level and required setups is not depended on the lead time in this evaluation scenario. The simulations also revealed that the relationship for the non-static mix scenario DM is close to the static one. Only the range of parts have a high influence in the considered relationship.

Small Bucket MRP

The evaluation of the MRP-based systems is by far more complex as these systems are influenced by the data quality and availability. In the parameter optimization of these systems, additional safety stock is added to the cycle stock used for planning. This safety stock is equally added in steps of 60 pieces to the whole range of parts produced in the line until the desired service level of 100% is reached (see Figure 5.27).

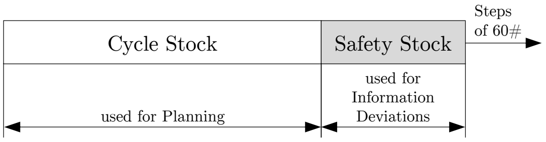

Figure 5.27: Definition of cycle and safety stock

Depending on the simulation settings, various parameter combinations are possible leading to different relationships between required setups and WIP. As a best case scenario for the small bucket MRP method, a setting with no data deviation is used. This scenario uses no additional safety stock because it is assumed that no changes in the forecast occur (NC) and the inventory data is of high quality (HQ). The result for this best case scenario, using a lead time of four hours and a planning cycle of one day, is shown in Figure 5.28.

Thereby, a clear advantage of the small bucket MRP over the kanban system can be seen. Again the range of parts has a high influence on the observed relationship while the demand mix only makes a small difference. As this best case scenario is not of practical use, detailed analysis of the influences of the considered data quality parameters are made in the next chapter.

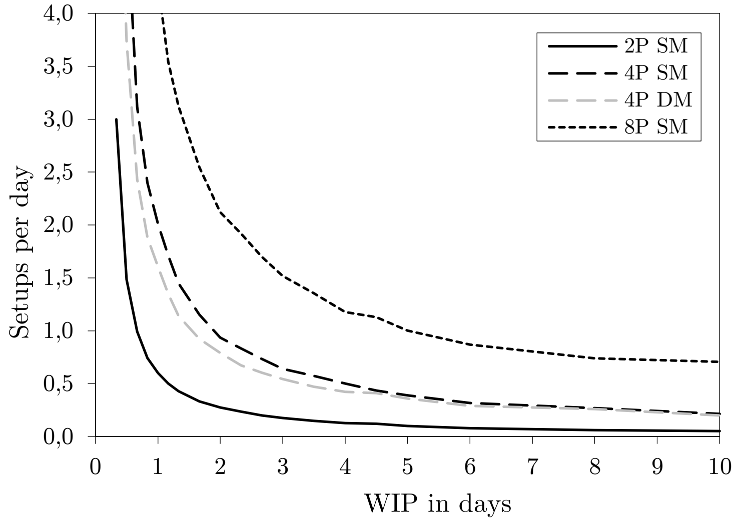

Figure 5.28: Small bucket MRP system in the ZV, NC, LT4, HQ, PC24 scenario[75]

In the small bucket MRP system, the range of parts has the highest influence on the required setups while the demand mix only shows a minor influence. In the best case scenario, the small bucket MRP system shows a significant advantage over the result of the kanban system.

Big Bucket MRP

The parameter setting of the big bucket MRP system is also complex. As the used algorithm has no parameter optimization loop such as the algorithm of the small bucket MRP (Figure 5.21), optimal lot sizes for different WIP levels have to be found first. In an iterative search algorithm which tries out different lot sizes in steps of 60 pieces for the different part ranges, the biggest possible lot sizes with which a service level of 100% can be reached are found. These lot sizes are later on used in the simulation of different data quality and availability scenarios. Thereby, like in the small bucket case using a parameter optimization, safety stock is added to the cycle stock until a service level of 100% is reached.

Figure 5.29 shows the results of the best case scenario of the big bucket MRP system. As the bucket size in the big bucket algorithm is one day, only WIP levels bigger than one day are possible. Furthermore, due to the algorithm itself, there is the limitation that the lot size cannot be bigger than two time steps. This leads to the case that, for example no evaluation data is available for the two part scenario (2P) beyond the three days WIP level. At higher WIP levels, the best case scenarios of the big bucket MRP approach show a better performance than the kanban solution, but these results are by far worse than the small bucket results.

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[75] based on data found in Appendix A2.2

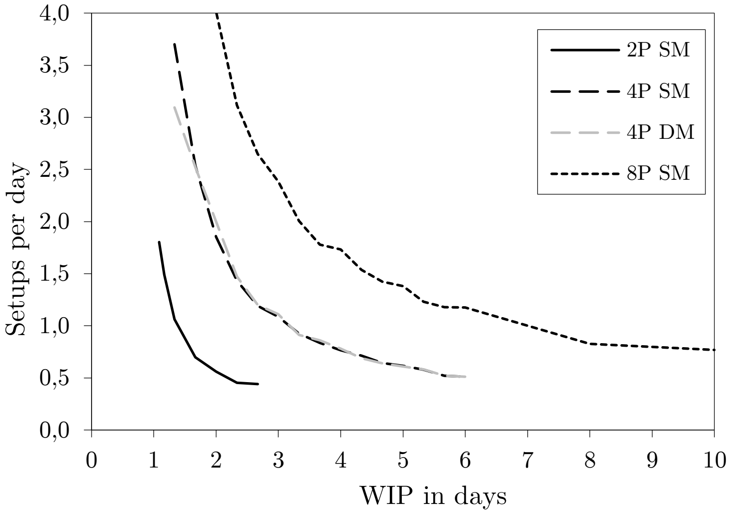

Figure 5.29: Big bucket MRP system in the ZV, NC, LT4, HQ, PC24 scenario[76]

In the big bucket MRP system the range of parts has the highest influence on the required setups. The big bucket MRP system shows an advantage over the kanban system, however, this approach is inferior to the small bucket MRP system.

5.3.2 Results

In addition to these best case scenarios, the impacts of the different informatization parameters are examined. This in-detail evaluation is done for the static four part scenario (4P SM) only. The other part range scenarios are evaluated with two selected case scenarios. As a benchmark in these evaluation, on the one hand the kanban results which are independent on the analyzed informatization parameters and on the other hand, the before shown best case scenarios of the small and the big bucket MRP are used.

Statistical Analysis

For all different scenarios numerous experiments with different WIP levels are evaluated. Due to the randomness of the modeled scenarios, several simulations have to be executed for one experiment. Afterwards, in a statistical analysis the mean values and the 95% confidential intervals of every experiment are calculated.

Figure 5.30 shows a statistical analysis of one of the simulated scenarios. The error bars in the chart show the 95% confidential intervals. As these confidential intervals are always below 10% of the mean values, only these mean values are used in the upcoming charts of this chapter.

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[76] based on data found in Appendix A2.3

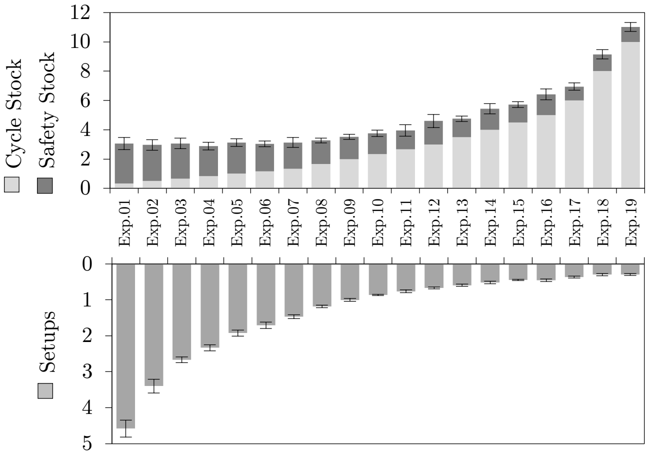

Figure 5.30: Statistical analysis with 95% confidential intervals of a evaluation scenario[77]

Forecasting Changes

The first analyzed parameter is the forecasting quality described in the simulation model with forecasting changes. As the lead time has an influence on the forecasting quality (see Figure 5.15), the impact of this parameter is analyzed.

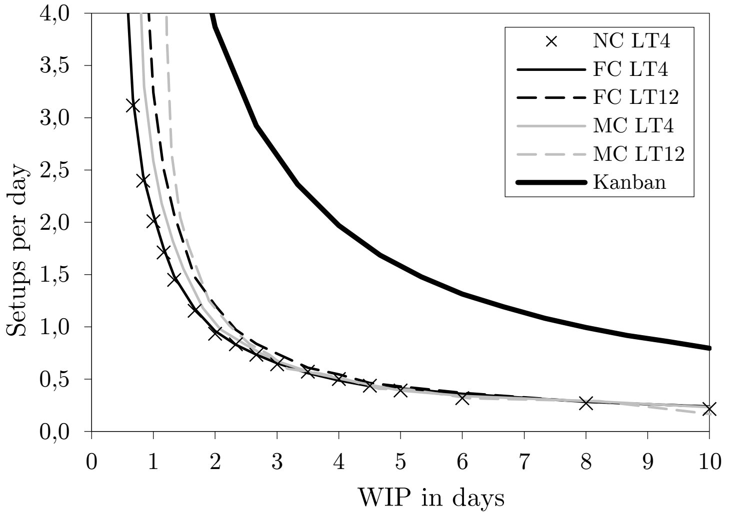

Figure 5.31: Small bucket MRP system in the ZV, 4P, SM, HQ, PC24 scenario[78]

The different forecasting scenarios and lead times only show a minor influence on the small bucket MRP system using a planning cycle of 24 hours.

Figure 5.31 shows the result of the evaluation of different forecasting scenarios using the small bucket MRP algorithm. With a planning frequency of 24 hours it can be seen that the 48 hours frozen period of the FC scenario (solid black line) leads to the same result as the best case scenario (x markers). The MC scenario

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[77] data from the evaluation scenario 4P, SM, MC, HQ, LT4, PC24 found in Appendix A2.5

[78] based on data found in Appendix A2.4

with a frozen period of 24 hours needs slightly more WIP for the same setup performance but the influence in general is marginal. The longer lead time scenario (LT12) requires in both forecasting cases a slightly higher WIP for the same amount of setups.

Data Availability

A more significant impact has the availability of data. In this evaluation, only the supply (internal) data availability is analyzed as it is assumed that the forecast (external) gets updated every 24 hours due to the standards of information sharing in the automotive supply industry.

Figure 5.32 shows the results of this evaluation for the small bucket MRP algorithm. As a representative of a real time production planning scenario, a planning cycle of one hour (solid black) is analyzed. It can be seen that this short cycle has only a minor improvement over the planning cycle of 24 hours (solid dotted), however it requires a high computation effort of the frequent planning activities. Therefore, only one experiment with such a short cycle is executed in this evaluation. Longer planning cycles (PC120) show a much worse performance depending on the forecasting changes. Hence, it can be deducted that the planning cycle has a high influence and its right selection based on the availability of data is a major concern.

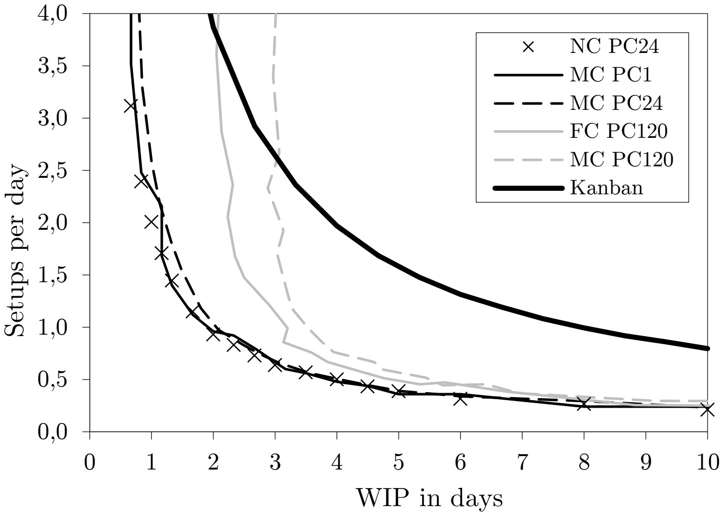

Figure 5.32: Small bucket MRP system in the ZV, 4P, SM, LT4, HQ scenario[79]
In the small bucket MRP system, the planning cycle has a major influence depending on the forecastability. The close to real time planning cycle of one hour only shows a minor advantage.

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[79] based on data found in Appendix A2.5

The evaluation of the planning cycle is also done using the big bucket MRP algorithm (see Figure 5.33).

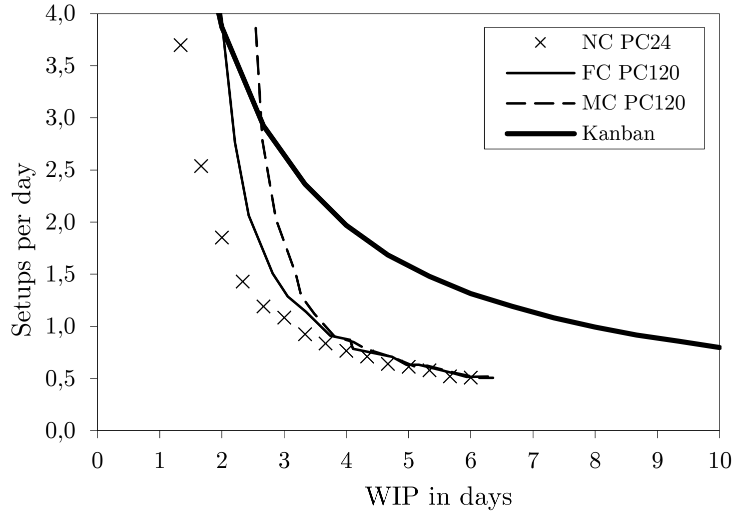

Figure 5.33: Big bucket MRP system in the ZV, 4P, SM, LT4, HQ scenario [80]

In the big bucket MRP system, the planning cycle also has a major influence depending on the forecastability. In comparison with the results of the small bucket MRP system, the big bucket MRP system even tend to have better results when planning cycles are long.

Thereby, it can be seen that the spreading between best case scenario and the results of the two forecasting scenarios using a planning cycle of 120 hours is not as high as with the small bucket MRP method through the already high base cycle stock of the big bucket MRP. Interesting is the fact that the performance of the big bucket MRP in comparison with the small bucket MRP in the MC forecasting scenario using a planning cycle of 120 hours is more or less equal, even with a slight better performance of the big bucket MRP algorithm. This leads to the assumption that the data availability and the model accuracy are related to each other.

Data Quality

As discussed in Chapter 3.3.2, data quality is one major aspect that will change due to the informatization of the shop floor. For the evaluation of the impact of this quality increase, the simulation scenario with no changes in the forecast was chosen and only different levels of the inventory data quality are analyzed using a planning cycle of 24 hours.

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[80] based on data found in Appendix A2.6

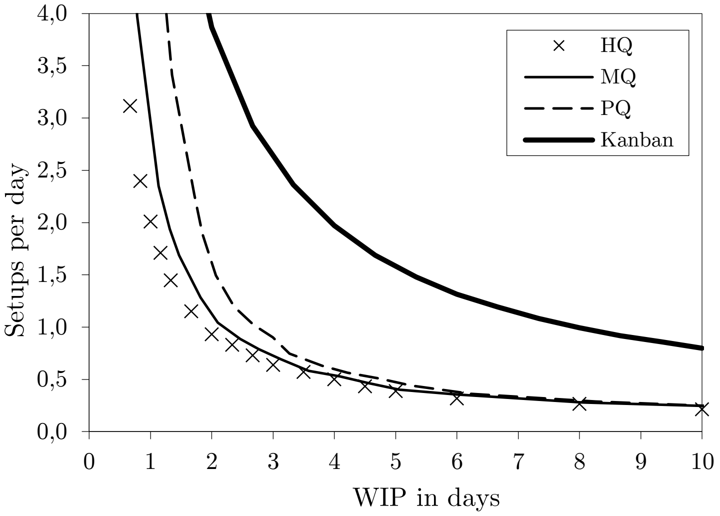

Figure 5.34: Small bucket MRP system in the ZV, 4P, SM, LT4, NC, PC24 scenario[81]

The different qualities of data show a minor influence in the small bucket MRP system.

Figure 5.34 shows the results of the evaluation using the small bucket MRP algorithm. The evaluation reveals that in this setting a poor data quality requires a higher WIP level. This means in general that for higher WIP levels a lower safety stock for data errors is needed.

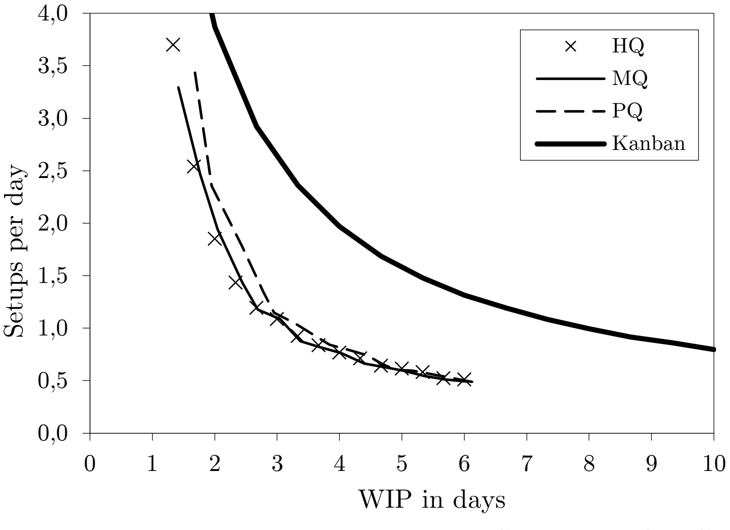

Figure 5.35: Big bucket MRP system in the ZV, 4P, SM, LT4, NC, PC24 scenario[82]

The big bucket MRP system shows nearly no influence by the data quality.

Figure 5.35 shows the results of the evaluation using the big bucket MRP algorithm. Thereby, the influence of data quality is by far weaker than in the small bucket case. In a medium quality scenario, more or less the same result can

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[81] based on data found in Appendix A2.7

[82] based on data found in Appendix A2.8

be achieved as in a high quality scenario. With the poor quality setting, only a little safety stock is needed to protect against data errors.

This leads to the insight that the detailed planning model used in the small bucket MRP algorithm requires in general a better data quality than the more abstract big bucket model. In comparison with the big bucket MRP algorithm, the small bucket MRP algorithm, even with poor data quality, has still an advantage.

Demand Variability

As all of the previous evaluations are only done with a part range of four, now the impact of the demand variability is analyzed. All these evaluations are executed with the forecast scenario MC. Thereby two major data quality scenarios are chosen in this evaluation. First, a scenario with medium data quality and a lead time of four hours. Second, the worst case scenario with poor data quality and a lead time of 12 hours. All the evaluations are performed with a planning cycle of 24 hours as well as a cycle of 120 hours. In this as well as all further evaluations only the small bucket MRP algorithm is used.

Figure 5.36 shows, the results of the evaluation of the impact of different ranges of parts. These charts show the high influence of the range of parts on the required amount of setups. While with a low external variability (two parts) the difference between the pull type PPC system (kanban) and the push type system (MRP) is only minor, at a high external variability, the push type system can demonstrate its superiority. These charts however also show that with long planning cycles (dotted line) and poor data quality the kanban system can be advantageous. Yet if a detailed PPC model is used with adequate data quality and the right planning cycles (solid line) its performance is outstanding.

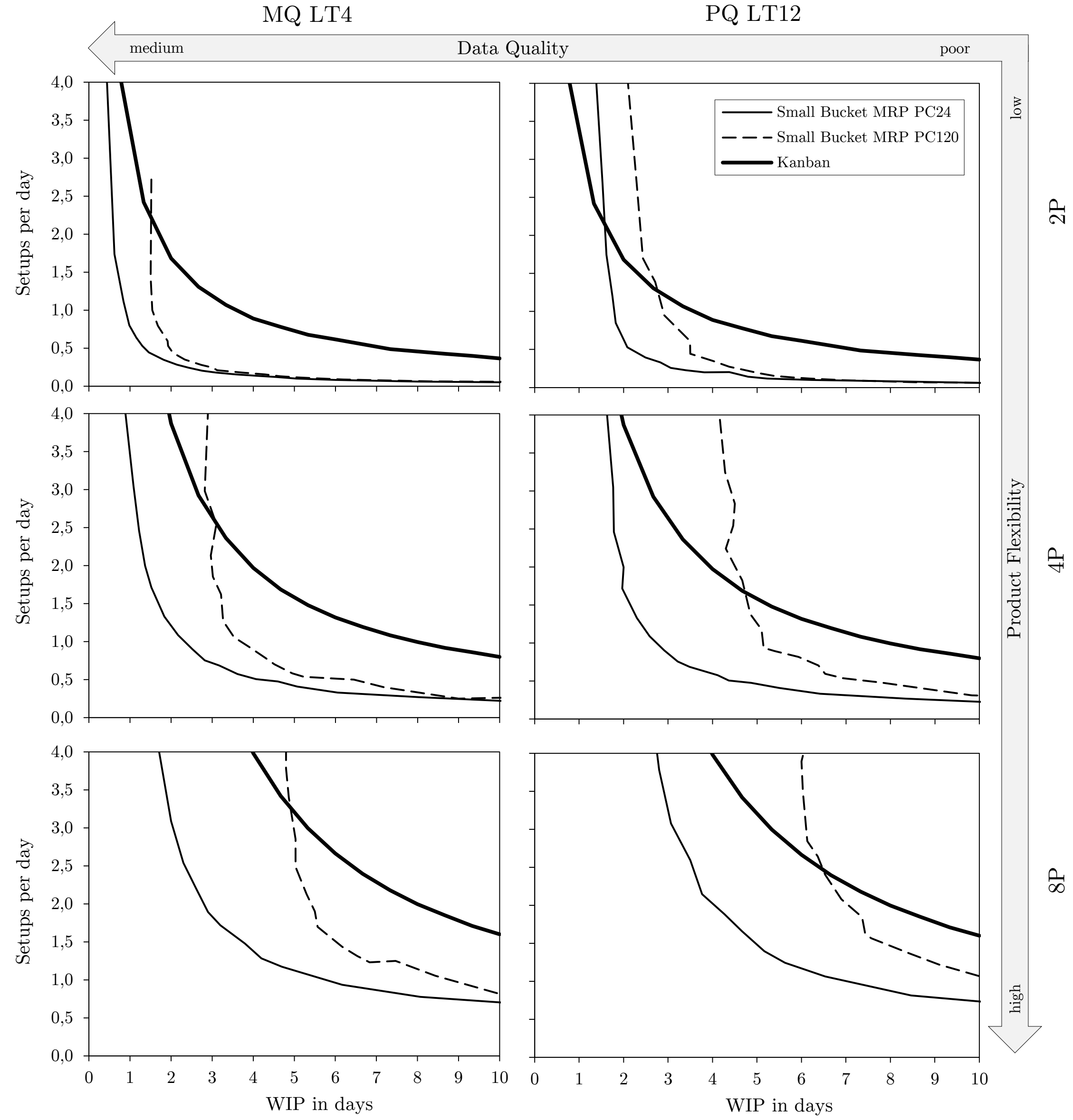

Figure 5.36: Comparison of different ZV, MC scenarios[83]

With a planning cycle of 24 hours (solid line), the push type small bucket MRP system shows its superiority over the pull type kanban system. Only when planning cycles are long (dotted line), the kanban system can be advantageous. The range of parts shows a high influence on the system performance. Especially at higher part ranges, the push type system can demonstrate its supremacy even when data quality is poor.

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[83] based on data found in Appendix A2.9 - A2.11

5.4 Evaluation of the Supply Variability

The aim of the second evaluation study is to evaluate the performance of the small bucket MRP system and the kanban system regarding their ability to handle a certain supply variability. In comparison to the first evaluation study the manufacturing model is now taking setup times and availabilities into account. The performance measure used in this study is the achieved service level at a certain WIP level.

5.4.1 Settings

In this evaluation, the ability of a single line to respond to a given demand under a certain supply variability is of interest. Table 5.5 shows the simulation settings of this scenario. The supply variability is modeled using different variability scenarios with different setup times (ST0.5, ST1, ST2) and mean times to repair (MTTR1, MTTR2). Again, in this evaluation study, the impact of the part range (2P, 4P, 8P) is analyzed. As the first study showed the minor impact of the demand mix, only the static mix (SM) scenario is evaluated in this evaluation. It is assumed that the internal data quality is of 100% (HQ) as the impacts of data quality were already analyzed in the first evaluation study. The first evaluation study also showed that the planning cycle of 24 hours (data availability) in combination with the MC forecast scenario fits well which is therefore used in this scenario.

	Characteristic	
Type	Internal (Supply)	External (Demand)
Flexibility	ST0.5, ST1, ST2	2P, 4P, 8P
& Variability	MTTR1, MTTR4	SM
Data Quality	HQ	MC
& Availability	PC24	update every 24h
Others	LT4	

Table 5.5: Simulation settings of the evaluation of the supply variability

Using these settings, the service level (see Equation (5.1)) at a given WIP level is calculated. Therefore, no further parameter optimization, as in the first study, is needed.

Kanban

As in the first evaluation study, a two container kanban system is also used in this one. In this scenario, however, there is a clear difference in the capacity usage of the manufacturing line. As discussed in the explanation of the manufacturing model (Chapter 5.2.3), only an average of 21 hours of a day are used for production. The line has, furthermore an average downtime of two hours per day. This leads to a maximum available setup time of one hour per day on average.

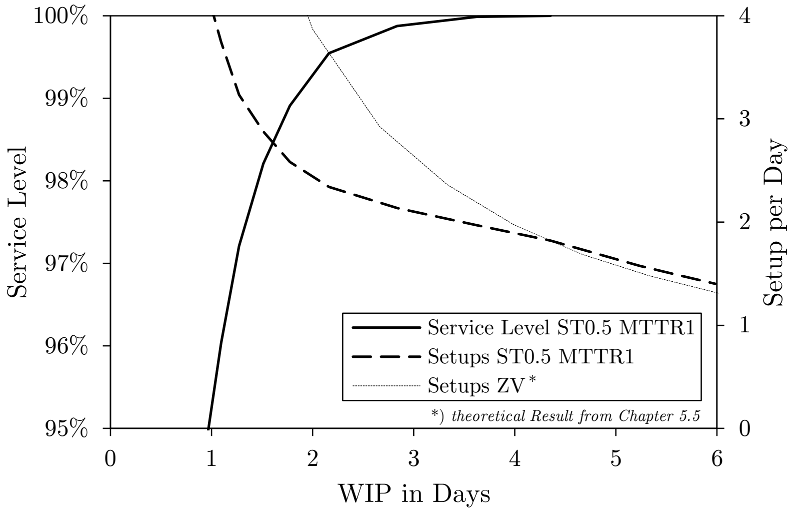

Figure 5.37: Kanban system in the SV, 4P, SM, LT4, ST0.5, MTTR1 scenario[84]

In the supply variability scenario using the kanban system, a certain container size and subsequently a certain WIP level is required to achieve the given capacity utilization (in this scenario a WIP level of four days). Below this level, there is a significant drop in the service level while above this level a service level of 100% can be reached and the characteristic of the required setups per day curve follows the theoretical zero variability curve.

Figure 5.37 shows the result of the required setups and the service level over the WIP level with four different parts in supply variability scenario with a setup time of 30 minutes (ST0.5) and an average recovery time of one hour (MTTR1). Thereby, the amount of setup of this supply variability scenario (black dotted) in comparison with the theoretical zero supply variability scenario (gray solid) is of special interest. Due to the small container sizes, more than two setups per day are necessary below a WIP level of four days. As in the above described capacity utilization, only one hour per day is available for setting-up. This leads to the significant drop of the service level (black solid) in that area. The required setups over the WIP curve is also shifted in this area (below four days WIP) until the required two setups per day are reached and the curve then follows the theoretical zero variability curve.

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[84] based on data found in Appendix A3.1

The utilization chart of Figure 5.38 for the individual simulation results show an equal result with the idle ratio. After a WIP level of four days (EXP08) is reached, the number of setups is low enough to enable an idle time at the manufacturing line. In all previous experiments (EXP01-EXP07) the setups proportion is higher than the available capacity for setting-up leading to a decline in the working proportion with the consequent drop in the service level.

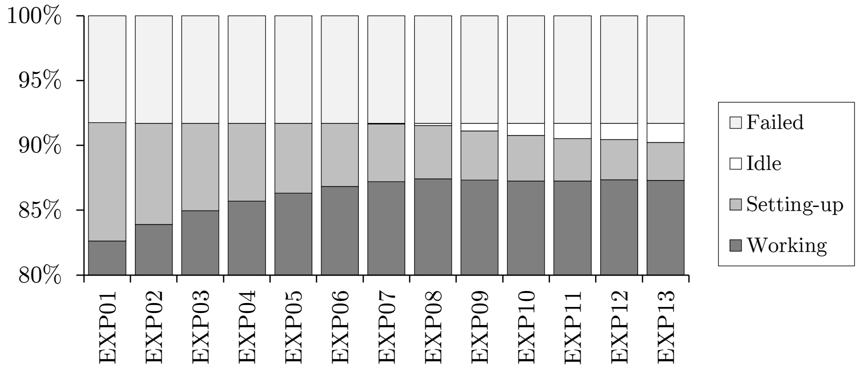

Figure 5.38 Utilization of the kanban system in the SV, 4P, SM, LT4, ST0.5, MTTR1 scenario[85]
In the EXP01-EXP07, the proportion for setting-up is higher than the reserved capacity for setting-up leading to a drop in the working proportion and consequently a decrease of the service level.

Small Bucket MRP

For the small bucket MRP system, in addition to the basic algorithm (see Figure 5.21) a WIP control is needed in this supply variability scenario. The MRP-based algorithm has to be enhanced in a way that only the amount of hours needed to reach the desired WIP level are used for production.

Figure 5.39 shows the used algorithm for the WIP control which includes a safety stock underride functionality in case of under capacity. This algorithm is used in addition to the already explained small bucket MRP algorithm (see Figure 5.19) and its parameter optimization algorithm (see Figure 5.21).

In the first step (1) of this algorithm, the current available operational inventory (minus the safety inventory) is read and stored in the variable $Stock_{TOTAL}$. The desired total inventory level $Stock_{TARGET}$ and the individual safety inventories for every part p $Stock_{SAFETY}(p)$ is also read. In the last action of the first step, the difference between the inventory target $Stock_{TARGET}$ and the actual inventory $\mathrm{Stock}_{\mathrm{TOTAL}}$ divided by the capacity of one day is calculated, rounded up and stored in the variable $t_{DIFFERENCE}$. This value indicated how many hours the actual inventory is below (positive $t_{DIFFERENCE}$) or above (negative $t_{DIFFERENCE}$)

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[85] based on data found in Appendix A3.1

the inventory target. In case of a value above four hours the safety stock underride function is executed (2).

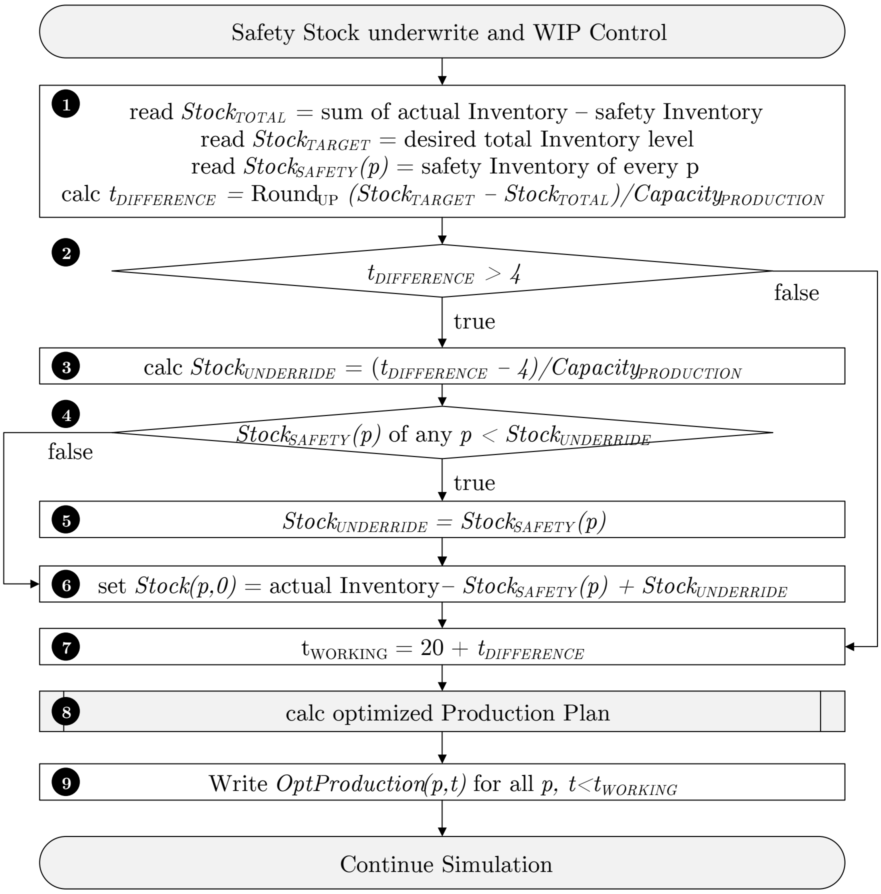

Figure 5.39: Flowchart of the WIP control of the small bucket MRP algorithm

Four hours is the threshold for this functionality because, in case of a small stock deviation, there is still a chance to plan with 24 hours of production of the upcoming day without harming the safety stock. In case of a higher backlog of the inventory, some safety stock is used as cycle stock and enabled thereby a lower number of setups. This then results in a fast rebuild of the inventory to the desired target. This procedure, nevertheless, also risks stock outs due to uncertain events. However, this stock underride is typically executed after a breakdown when the inventory level is low. Since it is uncertain that immediately after a breakdown a further breakdown again occurs, this stock underride overall contributes to a higher performance. In the first step of the stock underride function (3), the amount of pieces $Stock_{UNDERRIDE}$ needed to reach the target inventory is calculated based on the hours of overproduction. Then, for all parts *p,* the safety inventory $Stock_{SAFETY}(p)$ is checked if it is smaller than $Stock_{UNDERRIDE}$ (4) and in case of a smaller value, the $Stock_{UNDERRIDE}$ is set to this value (5). Finally, the new stock level for all parts p is calculated (6) based on the $Stock_{UNDERRIDE}$.

Afterwards, the amount of hours of production $t_{WORKING}$ in the upcoming day is calculated based on the 21 hours of production on average and the already calculated $t_{DIFFERENCE}$ (7). Next, the parameter optimization algorithm including the core small bucket MRP algorithm is executed (8) and finally the production plan for the upcoming day is written until $t_{WORKING}$ (9).

Using this WIP control in the small bucket MRP algorithm, various simulations with different cycle and safety stocks (compare Figure 5.27) are executed. The used cycle stocks (CS) are chosen based on the setup characteristic curves from Chapter 5.3.

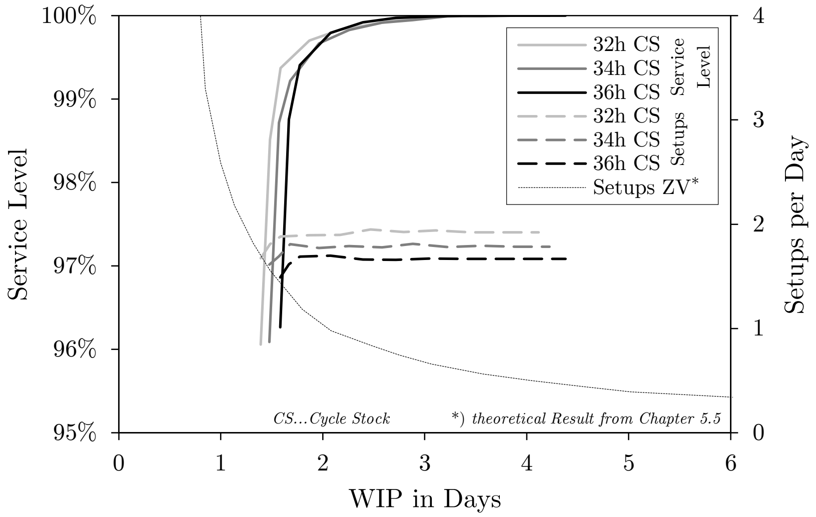

Figure 5.40: Small Bucket MRP in the SV, 4P, SM, LT4, ST0.5, MTTR1 scenario[86]
The service level characteristic of the small bucket MRP method tends to be robust for different cycle stock settings close to the optimum one. Furthermore, the service level curve shows an advantage over the characteristic of the kanban system.

Figure 5.40 shows the service level and required setup curves for different cycle stock settings. With a cycle stock of 32h (light gray), the target of two setups per day is achieved. However, as the service level curves show, higher cycle stock settings (34h, 36h) also tend to a similar characteristic which leads to the assumption that the used small bucket MRP-based method is robust against small deviations from the optimal cycle stock setting. The service level curves of Figure 5.40 furthermore show an advantage over the characteristic of the kanban system.

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[86] based on data found in Appendix A3.2

5.4.2 Results

As in the previous evaluation the in-detail analysis of different supply variability settings is done for the static four part scenario (4P SM) only. Other part range scenarios are evaluated only with the MTTR1 scenario and different setup times.

Statistical Analysis

For all different scenarios, numerous experiments with different WIP levels are evaluated. Due to the randomness of the modeled scenarios, several simulations have to be executed for one experiment. Afterwards, in a statistical analysis the mean values and the 95% confidential intervals for every experiment are calculated.

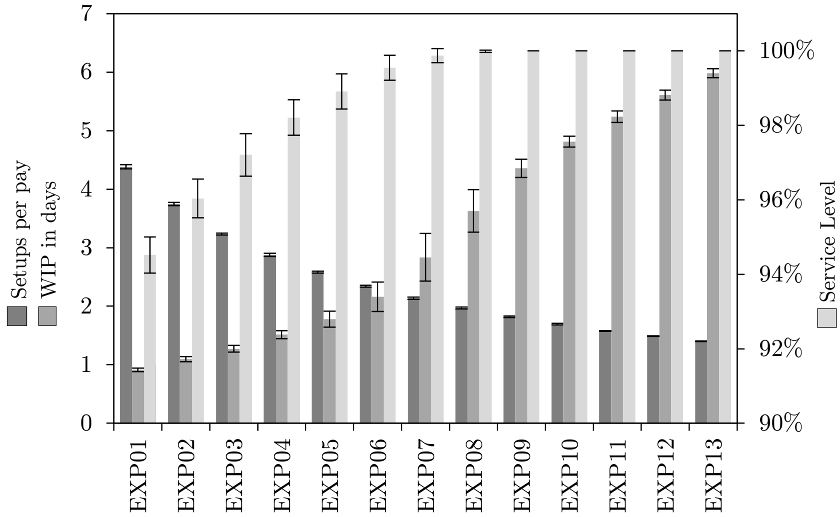

Figure 5.41: Statistical analysis with 95% confidential intervals of a evaluation scenario[87]
Only the WIP level shows higher confidential intervals especially
in the area when the service level is reaching 100%.

Figure 5.41 shows a statistical analysis of one of the simulated scenarios. The error bars in the chart show the 95% confidential intervals. Only the WIP levels show considerably high confidential intervals (EXP07) when the service level is close to 100% while all other confidential intervals remain small. Therefore, only the mean values of the experiments are used in the upcoming charts of this chapter.

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[87] based on data from the kanban evaluation scenario SV, 4P, SM, LT4, ST0.5, MTTR1 found in Appendix A3.1

Setup Time

The length of the changeover has a major impact on the systems performance. As the capacity usage is given in this model, only an average of one hour per day can be used for setting-up. Depending on the setup time, this leads to a maximum of allowed amount of setups per day.

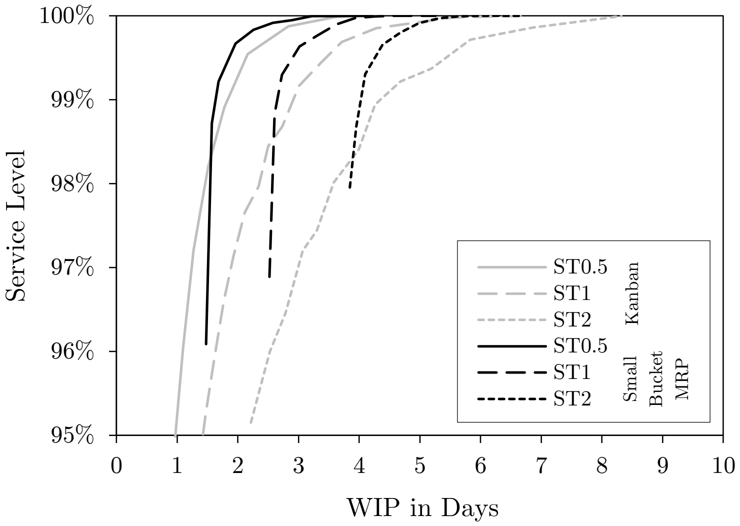

Figure 5.42: Results of the SV, 4P SM, LT4, MTTR1 scenario[88]
The small bucket MRP method has an advantage over the kanban system in reaching better service levels at lower WIP especially when setup times are long.

Figure 5.42 shows the service level characteristic of the used push (small bucket MRP) and pull (kanban) type methods. For all setup times, there is an advantage of the MRP-based method with a clear trend to a much better performance when the setup time is long. The reason why the kanban system needs fewer WIP than the small bucket MRP system at low service levels is due to the setting of the push type method. In these experiments, the cycle stock was set to achieve an optimal behavior close to a 100% service level, however other settings (lower cycle stocks) are also possible which would then show a different behavior at lower service levels.

Supply Variability

The supply variability, due to machine breakdowns, show a significant influence on the service level of the system. In comparison to the scenario of Figure 5.42, with a MTTR of one hour, a supply variability with a four times longer MTTR is analyzed in this scenario.

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[88] based on data found in Appendix A3.3 - A3.8

Figure 5.43 shows that the kanban system tends to need a much higher WIP to achieve a 100% service level in comparison to the scenario with a MTTR of one hour. The small bucket MRP system also needs a higher WIP in this scenario but the increase is by far not that big as with the kanban system. This leads to the insight that, especially in environments with high supply variability, a well-adjusted push type system is dominating the kanban system.

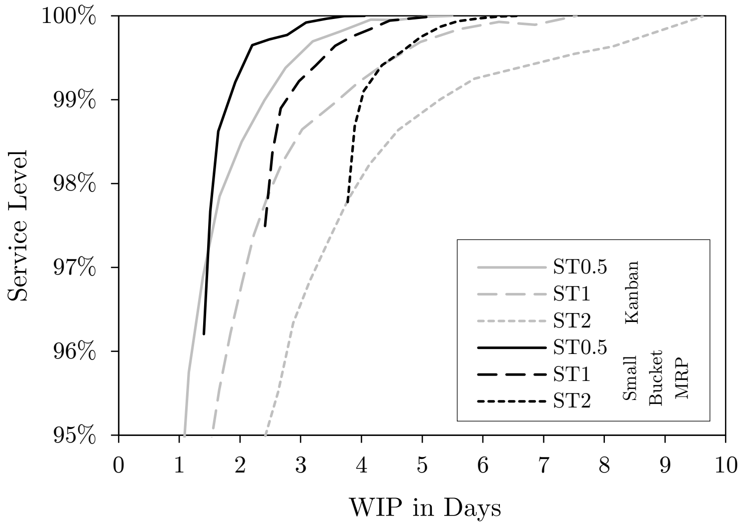

Figure 5.43: Results of the SV, 4P SM, LT4, MTTR4 scenario[89]

Especially when supply variability (MTTR) is high the small bucket MRP system is dominating the kanban system.

Demand Variability

As the previous scenarios are only done with four different parts, the influence of the part range in combination with the supply variability is also analyzed. As the previous scenarios showed that the length of the setup time is the most significant factor in the supply variability, this factor is mostly of interest in the evaluation of different part ranges. Figure 5.44 shows the results for the different part ranges scenarios for the kanban and the small bucket MRP system. In the two part and four part range scenarios, the three different setup times are evaluated while in the 8 part scenario only the 30 minutes and the 60 minutes setup times are analyzed because the 120 minutes setup time scenario is out of the WIP scope of this evaluation.

Figure 5.44 shows the results for the different part ranges using a MTTR of one hour. In all three cases, a clear trend towards a better performance of the small bucket MRP-system can be seen when the setup times are long. In scenarios with only a few products and short setup times (2P SM, ST0.5), the MRP-based

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[89] based on data found in Appendix A3.3 - A3.8

method still has its advantages. On average over all 8 analyzed settings, the small bucket MRP-based system needs 36% less WIP[90] to reach 100% service level than the kanban system.

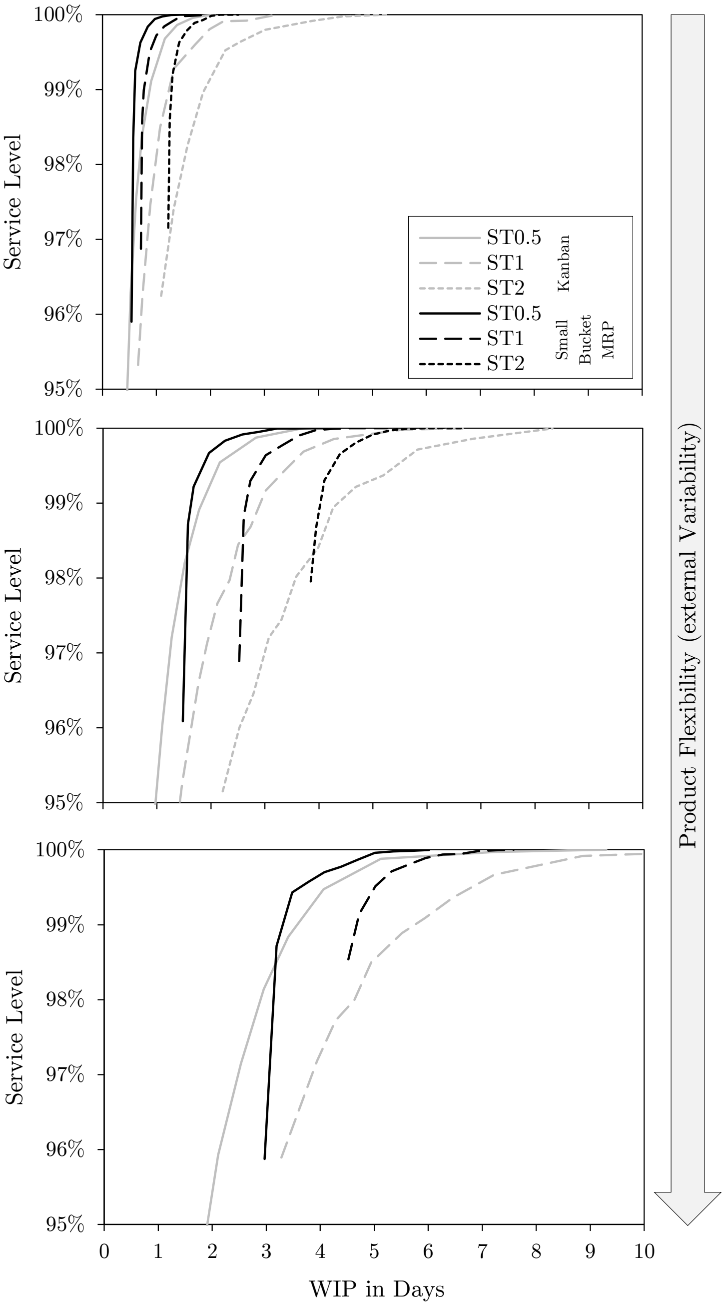

Figure 5.44: Comparison of different SV, MC, MTTR1 scenarios[91]

In all analyzed scenarios, there is a clear trend towards a better performance of the small bucket MRP-system when the setup times are long or when product flexibility is needed.

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[90] 95% confidential interval ±8%

[91] based on data found in Appendix A3.3 - A3.18

6 CHAPTER

Discussion

> *The greatest danger in times of turbulence is not the turbulence; it is to act with yesterday's logic.*
>
> Peter Drucker (1909 - 2005)

Based on the results of the simulation based evaluation study of Chapter 5, this chapter provides a complete overview on the found insights. Furthermore, these insights are used to enhance an existing PPC configuration framework and a best practice approach focusing on the overall total costs is suggested. Moreover, a use case example of the configuration and implementation of a PPC system in the automotive transmission production is given. Finally, the lessons learned from the practical use case are discussed.

6.1 Insights

The research using the simulation based evaluation study showed to be a valued approach in the understanding of the influencing factors in PPC. Furthermore, the used required setups over WIP curves proved to be a simple and useful way in the characterization of a PPC system. The gained insights in the evaluation study of the PPC selection problem of disconnected flow lines are the following:

Solvability of PPC Models

Even nowadays, the solvability of the easy to formulate but burdensome to solve PPC LP models is still problematic. This is especially true when the problem size is big due to a high number of different parts and a large number of planning time steps. The used heuristics in this evaluation study showed to be a good alternative. Thereby, especially the use of the inventory ranges turned out to be a powerful and simple formulation that can be solved close to optimality in just a few milliseconds.

PPC Model Accuracy

Models are always only a limited representation of reality. In the process of model building delimitation, reduction, decomposition, aggregation and abstraction are used to capture the major elements and influencing factors of the complex reality. Several different PPC models with different accuracies regarding their representation of time, the used mechanisms for lot sizing, the capacity consideration etc. exist. In the evaluation study, two contrary PPC models with different modeling approaches for the planning time where analyzed. The simulations showed that data availability and PPC modeling accuracy are related to each other. The simple and abstract big bucket time model showed a slightly better performance when data availability was bad. On the contrary, only the more detailed small bucket time model could use the advantages of high data availability. This phenomenon can be explained using the law of requisite variety of Ashby (1956). For the investigated focus area, it can be deducted that the model complexity of the control system (PPC model accuracy) is corresponding to the through data known complexity (data availability) of the controlled manufacturing environment.

Data Availability

The on-going informatization will dramatically increase data availability on the shop floor and in the supply chains. In PPC, mainly the inventory and demand data availability will be influenced. The prior insight regarding the PPC model accuracy already pointed out that this availability increase must go hand in hand with more detailed planning models. Otherwise no significant efficiency benefit can be achieved from this trend. The evaluation study, furthermore, showed that real time availability of data is only partly necessary, especially when only a part of the data (e.g. inventory data) is available in real time while other data, which is relevant for planning (e.g. demand data), is only updated every day. In such a case no real performance gain was measured in the simulation results.

Data Quality

Beside the availability of data, the quality of the data, measured in this evaluation by the inventory inaccuracy, will also increase through the informatization. Deviations between the data in information systems and the real inventories on the shop floor have to be buffered using additional safety inventory. The simulations using different inventory inaccuracies showed that in-detail PPC models are more sensitive to deviations in the stock levels than simple planning models. This effect is mainly attributable to the already higher inventory levels of the simple PPC models in comparison with the more sophisticated models which can run with the same settings at a lower stock level. Consequentially, in-detail PPC models need more safety inventory to protect against the inventory inaccuracies than simple models.

Product Flexibility

The by the customer demanded mass customization of products is driving the product variety to new limits. This trend is not for free and requires that production systems become even more flexible. Beside the required volume flexibility which is mainly influencing mid-term aggregate planning activities, the product flexibility is a major concern on the operational level of PPC. The demand mix flexibility was also analyzed, but it turned out that this flexibility dimension has only minor influence on the PPC system performance. However, the evaluations showed that the range of products has a high influence on the performance of the planning system. Especially the kanban system showed only limited applicability when high product flexibility is needed. Only with a range of two different products, the kanban system delivered a performance which was close to the performance of more advanced systems. In all other cases, a clear dominance of the more sophisticated small bucket MRP-based approach could be seen, especially when the data used is of adequate quality and availability.

Supply Variability

The supply variability is of major concern in the selection of the right PPC strategy. In this evaluation study, the two major sources of supply variability, breakdowns and setups, were analyzed. The simulations showed that especially the length of the setup time is an extremely crucial factor in PPC. When setup times are long the kanban system exceptionally shows a minor performance in comparison to the used small bucket MRP-based system. Supply variability, due to different mean time to repair after breakdowns, have to be buffered using safety inventory in any PPC system. The evaluation results showed that kanban systems tend to need more safety stock than well-adjusted MRP-type systems.

PPC Settings

The evaluation study furthermore showed that finding an optimal setting for an MRP-based PPC system can be challenging. Especially more detailed models tend to need a greater set of parameters which have to be well-adjusted. This stands in stark contrast to the easy to adjust kanban system. However, once a kanban system is adjusted, a continuous automated optimization to changing market condition is not possible due to the decentralized nature of the system. In contrast, in MRP-based systems automated parameter optimization can be executed in every planning run, which can be a powerful weapon in a volatile market environment.

6.2 Best Practice

The selection of an optimal PPC configuration is a complicated task which depends on several factors and needs to be taken, especially in the rapidly changing economic environment, more and more frequently. An interesting approach for the selection of the right PPC strategy can be found in the teaching paradigm information/control/buffer portfolio by Schwarz (1998). This framework analyzes different PPC strategies in the dimensions information system, control system and buffer system. The control system contains the decision rules and is responsible for the implementation of the decisions. The information system contains all required historical, future-oriented and current status information for decision making in the control system. Moreover, the framework considers the required buffer (inventory, service level, capacity, etc.) to run the system based on the control and the information system. According to Schwarz (1998), an operation must select the PPC strategy based on the total costs of these three components.

> *In selecting the best I/C/B portfolio, the object is not to select either the best possible information system, control system, or buffer system, but to select the portfolio with the minimum possible total costs where total I/C/B costs = total information system costs + total control system costs + total buffer system costs. (Schwarz, 1998)*

This framework provides an elegant solution for the PPC decision problem by combing the different dimensions on the common measure costs. Based on these three dimensions, several scenarios are possible. On the one hand, an operation for which inventory buffering is cheap might be better advised to run the system using a simple PPC system which needs only few information than to use an expensive information and control system. On the other hand, an operation for which buffering is also expensive should better invest in an information and control system to keep the costly inventory down.

6.2.1 PPC Selection Approach

The same logic can also be used for the PPC configuration problem in the flow shop manufacturing environment. However, the evaluation study showed that the I/C/B portfolio needs to be updated in some of the dimensions to fulfill present needs. The main drawback of the I/C/B framework is the missing consideration of the requisite flexibility of the manufacturing system based on the customer requirements. The simulations showed that the product range has a major impact on the performance of a PPC system in respect to the required WIP level for a certain amount of setup per day. Furthermore, the evaluation study showed a relationship between data availability and PPC model accuracy. These insights lead to the extension and adaption of the I/C/B decision framework. Figure 6.1 shows these enhancements in the suggested PPC selection best practice approach.

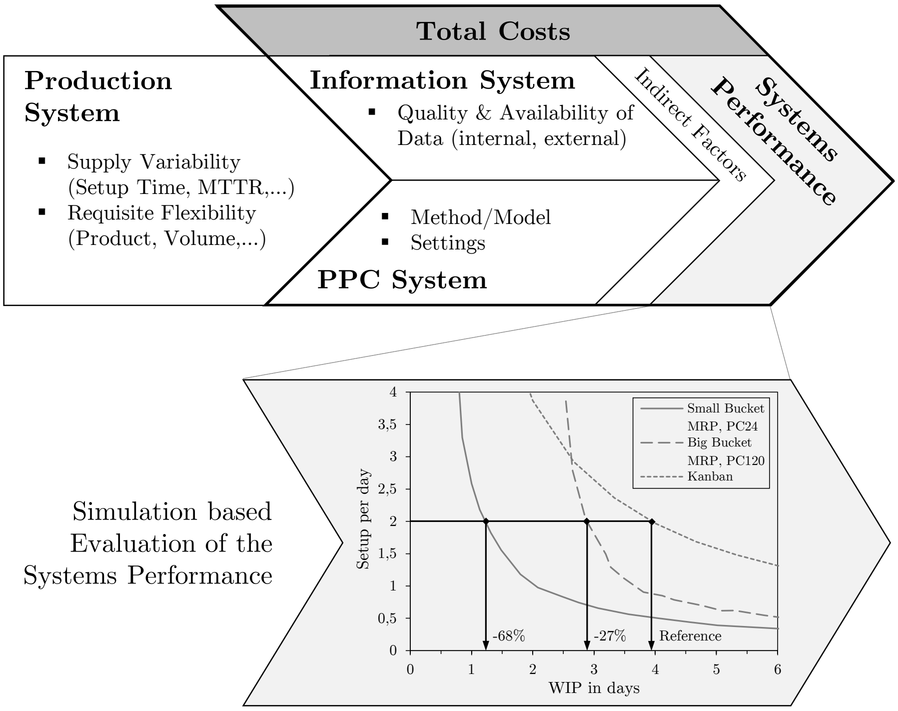

Figure 6.1: Suggested PPC selection best practice approach

The selection of the optimal PPC design and configuration should be based on the total costs for the information system, the PPC system, the systems performance and the costs for indirect factors. The characteristics of the production system act as an input in this selection approach.

This framework is grounded on three basic systems: the production, information and PPC system as well as indirect factors covering knowledge impacts. The systems performance results out of the design and the interactions between these factors.

Production System

The production system is mainly characterized by its supply variability and the requisite flexibility. The supply variability includes effects from setting up, breakdowns, quality defects and so on. The requisite flexibility originates from the customer requirements in terms of product variations and delivery time expectations. The evaluation study showed that these factors have an overall major impact on the performance of all PPC approaches. The requisite flexibility has higher influence on some of the PPC methods and on others less. Despite the PPC selection best practice, standard measures using lean tools and complexity management approaches to control these highly influencing factors have to be taken. However, these factors act as an input for this best practice approach.

Information and PPC System

The configuration of the information and the PPC system form the major challenge in the selection process. Unlike the I/C/B framework, the information and the PPC system are not considered separately due to the interactions shown in the evaluation study between these two systems. The quality and availability of external (customer) and internal (supply) data have remarkable influences on the selection of a fitting PPC model.

Indirect Factors

Despite the direct factors of the production, information and PPC system, indirect factors also have an influence on the systems performance. These indirect factors can be mainly attributed to the required skill and knowledge level for the different PPC methods. Especially pull type PPC systems require a certain discipline and responsibility on the shop floor to operate properly.

Systems Performance

Overall it can be said that these factors result in a performance of the system with a certain use of the different buffering systems to match the demand (compare Chapter 2.3.2). As the evaluation study showed, simulation is a key technique to reveal the performance. Figure 6.1 shows an example of this approach for a production system with four different parts and the capacity of doing two setups per day. The three different PPC strategies, small bucket MRP with a planning cycle of 24 hours, big bucket MRP with a planning cycle of 120 hours and kanban are analyzed in the simulation. The simulation reveals that, in comparison to the kanban system, significant WIP reductions can be achieved by using one of the MRP based systems. However, in the end, these WIP reductions have to be converted to savings and the total costs have to be analyzed.

Total Costs

The decision on the optimal PPC design and configuration should be based on the overall system costs for the information system, the PPC system, the resulting system performance and the costs for the indirect factors. It can turn out that, in the simulation example of Figure 6.1, the kanban system would be the overall cost optimum when the inventory keeping is cheap. However, depending on this costs, it can also make sense to invest in a PPC system using an in detail model and high quality data. Another aspect in the PPC decision is the development of costs especially for the information system. Driven by IoT and its associated technologies, there is an ongoing decrease in the costs for high quality information.

6.2.2 Use Case Example

Case Description

The case company is a transmission manufacturer of an OEM, which produces 5-speed and 6-speed manual gearboxes. The company is located in Spain and integrated into the global supply chain network of the OEM. About half of the production goes to various national assembly lines of the OEM in Spain. The other half of the production is shipped globally with a great extent to Germany. Beside the assembly of the transmission, nearly all production steps which are needed for the processing of the transmission components are done in-house. The company furthermore produces spare parts of gearbox component like gears and shafts which are not series products any more.

The main objective in this use case example was to increase the utilization of the assembly. The occurrence of missing parts at the assembly line should be decreased through an assembly plan which is verified throughout the whole production network. This would result in a much higher planning stability and lesser replanning activities ("firefighting").

Production System

The case company produces over 30 different variations of gearboxes which differ in the transmission ratio, the surface finishing quality and the number of speeds. Table 6.1 shows the product variety of the gearbox and its components.

Part	Different Parts	Total Varieties
Gearboxes	-	>30
Shafts	2	>20
Fix gears	4	>30
Free gears	6	>40
Final drives	1	>10
Housings	2	>20

Table 6.1: Typical number of varieties of the main parts

A 6-speed gearbox consists of 15 main components in total: two shafts, four fix gears, six free gears, one final drive and two housings. The high variety of transmission also drives the number of varieties at the component level. Therefore, over 120 different components in total have to be produced. The challenge for PPC arises due to the fact that a gearbox can only be assembled if all components are available in the right quantity at the right time.

The production process of the components is multi-staged and interconnected. Characteristically for the automotive industry, the operations are performed by highly automated production lines, which consist of several machines linked using conveyor systems. The production process is characterized by long manual setup times in the machining area and long meantime to repair.

Initial Information and PPC System

Typically for the automotive industry, the demand is exactly known on a daily basis in the frozen period due to delivery call-offs and in the further planning period with a high degree of certainty. As an internal information system, no IT-based system existed. Instead all the inventories got counted once per day. This information was then used by the foremen to decide which parts have to be produces. Driven by the OEMs production system philosophy, the case company also has a kanban system. As a result of the high number of types, the kanban system needs a far too high stock level to work properly. Therefore, a kanban manager was constantly adjusting the amount of kanban cards to the weekly production mixes. The overall planning process of the transmission case company was uncoordinated and depending on a few men who acquired enough experience to control the system.

New Information and PPC System

Based on the fundaments of the initial information system, a new PPC system was developed. Through the minor IT-penetration of the shop floor, data quality and availability was obviously bad. Applying the insights of above, a simple big bucket MRP based PPC system with a bucket size of one shift (8 hours) was used. This planning tool also included algorithms for finite capacity planning and the consideration of setup times. Using a simulation optimization approach, the tool was then extended by an assembly planning algorithm which uses the production simulation to evaluate the assembly schedule. Figure 6.2 gives an overview of the implemented planning tool named GESPRO. The operational use showed an increase in the quality of the inventory data. This can be mainly attributed to the systematic planning logic, as it is more depended on hard numbers than the prior decision making by the foremen. The new quality of data then led to the demand of a more accurate planning model which ended in the adaption of the bucket size from 8 hours (on shift) to a 4 hour model. The implementation of the planning tool furthermore shows the importance of the development and establishment of a culture which creates confidence in the proposals of the planning system. The use case example shows that the complex planning problems often do not allow to understand the proposed result at first glance. Therefore, it is desirable to develop a system which is intended to support and in which the planner has the ultimate decision-making power.

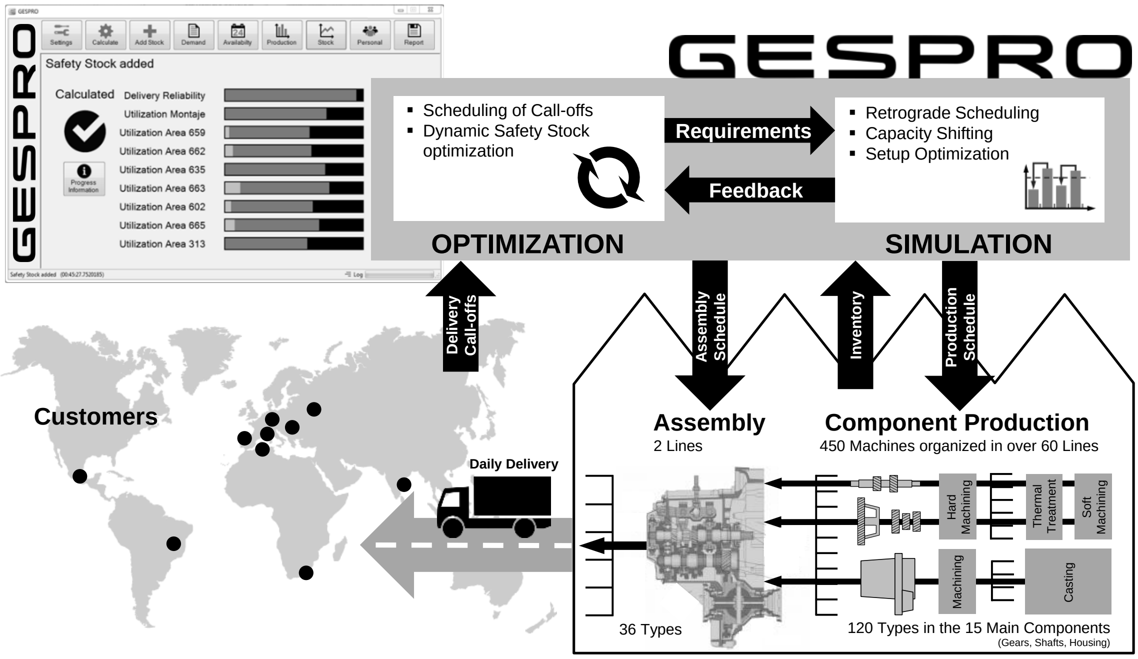

Figure 6.2: Overview of the planning tool GESPRO

Overall it can be said that the use case example shows that the systems performance increase without any investments in the information system. However, there is still the possibility for further development of the planning system when new information technologies are used to capture inventory data in more detail. Nevertheless, at that point in time, the overall cost optimal solution was the introduced semiautomatic planning solution.

6.3 Lessons Learned

The field of PPC is strongly coined by thoughts of a close to religious level of on the one hand the lean and on the other hand the IT believers. These two faith groups are highly convinced of their worldview with only little scope of dialogue. However, science and also practice shows us that IT is no muda[92] and we need collaboration between these two movements. Both the information and the planning system must be selected wisely to ensure a cost optimal overall performance. Another often claimed requirement for a PPC system is the traceability of the planning decisions. Therefore, visual representations of the planning results can be especially useful. Another aspect is the possibility and the incentives for continuous improvements of the PPS system. Furthermore, the human integration in the decision making is an important issue. The trend to autonomous decision making might have negative aspects on the cognitive skills of a production planner. Nowadays, the production planner has results of predictions and decisions of the past in his head, which will be useful for his future actions. These mental response relationships might get lost in fully autonomous operated systems and in case of extracurricular events, a human might not be able to take over the decision making task any more.

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[92] Muda (無駄) is a Japanese word meaning futility; uselessness; idleness; superfluity; waste; wastage.

CHAPTER

7 Conclusion

Thinking is the hardest work there is, which is probably the reason why so few engage in it.
Henry Ford (1863 – 1947)

After years of lean production, a new hype is flooding the manufacturing industry. Informatization of the shop floor and the supply chains using IoT and several associated enabling technologies is now the rage. Several initiatives such as the Physical Internet, the Industrial Internet or also Industry 4.0 were started and have the attention of the top management. Consultants and white papers promise significant efficiency increases[93] through the new possibilities of informatization in manufacturing. Several companies expect a better production planning and control and a higher flexibility through the increasing availability of high quality data. It is expected that powerful, autonomous algorithms will control the production based on the available real time information and will directly interact with the machines as CPS in the future.

Nevertheless, the production planning and control real life, especially in the automotive supply industry, is nowadays a totally different one. I experienced that after years of consulting, many production planners acquired a strong believe in one of the two big production paradigms push and pull, without an in-detail

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[93] according to a Strategy& and PricewaterhouseCoopers (2014) study the annual increase in the resource efficiency will be 3.3% on average across all industries.

understanding of the underlying methods and the influencing factors. Furthermore, information quality is still far away from high quality and real time. As a result of the often poor data quality, PPC decisions are based on averages or estimates and simple planning models which then results in inaccurate planning results. This discrepancy of the inventory and demand data between information systems and the real physical flow of goods is a well-known phenomenon.

7.1 Research Question

This thesis presents a simulation based evaluation study which analyzed the impacts of informatization on PPC. This evaluation shows that real time information is not absolutely necessary. A relation between modelling accuracy and data quality can be seen. Without the right planning model, real time data can be worthless. The simulation based analysis of the PPC systems behavior proofed to be a valuable approach in the selection of the right PPC setting for a given production system. In the evaluation, it turned out that especially the product flexibility plays a major role in the selection of an appropriate PPC strategy. The evaluation results also show that significant improvements can be achieved by using the right planning model and the right settings. I think that a shift away from the stereotypical thinking of push or pull type PPC systems towards an understanding of the underlying algorithms and the influencing parameters is necessary. The insights and the presented best practice for the selection of the right PPC strategy of Chapter 6 are a valued step on the road to this understanding.

7.2 Further Research

Nevertheless, further research in this area is necessary. One potential topic is the hierarchy of the PPC decision making. The analyzed methods in this thesis are focusing only on one specific line. Due to the limitations of the used simulation model, it was not possible to evaluate the network behavior of these different methods. Thereby, the trend to more decentralized decision making instead of the classical centralized top down approach is of special interest. I assume that there is the demand of both elements, centralized and decentralized, in PPC. The right amount of these elements and the overall design must be investigated in further research activities.

List of Figures

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List of Abbreviation

APS	Advanced Planning System
ABM	Agent based Modeling
APICS	American Production and Inventory Control Society
AI	Artificial Intelligence
BOM	Bill of Material
BTF	Build to Forecast
BTO	Build to Order
BPR	Business Process Reengineering
CRP	Capacity Requirements Planning
CAD	Computer aided Design
CAE	Computer aided Engineering
CAM	Computer aided Manufacturing
CAPP	Computer aided Process Planning
CAQ	Computer aided Quality
CAx	Computer aided System
CIM	Computer Integrated Manufacturing
CLSP	Capacitated Lot Sizing Problem
CONWIP	Constant Work in Process
CPPS	Cyber Physical Production System
CPS	Cyber Physical System
CT	Cycle Time
DAI	Distributed Artificial Intelligence
DES	Discrete Event Simulation
DIN	Deutsche Industrie Norm
DLSP	Discrete Lot-Sizing and Scheduling Problem
DMU	Digital Mock UP
EOQ	Economic Order Quantity
EDI	Electronic Data Interface
ERP	Enterprise Resource Planning
EPEI	Every Part Every Interval
FIFO	First In First Out
FOP	Fixed Order Period
FOQ	Fixed Order Quantity
FMS	Flexible Manufacturing System
GSP	General Simulation Program
GA	Genetic Algorithms
GDP	Gross Domestic Product

ICT	Information and Communication Technology
IDC	International Data Corporation
IT	Information Technology
IA	Intelligence Amplification
IMS	Intelligent Manufacturing System
IoT	Internet of Things
JIT	Just in Time
KPI	Key Performance Indicator
LP	Linear Programming
LFL	Lot for Lot
M2M	Machine to Machine
MTO	Make to Order
MTS	Make to Stock
MES	Manufacturing Execution System
MRP II	Manufacturing Resource Planning
MPS	Master Production Schedule
MRP	Material Requirements Planning
MAE	Mean Average Error
MAPE	Mean Average Percentage Error
MTTF	Mean Time to Failure
MTTR	Mean Time to Recover
NFC	Near Field Communication
OM	Operations Management
OR	Operations Research
OPT	Optimized Production Technology
OTD	Order to Delivery
OEM	Original Equipment Manufacturer
OEE	Overall Equipment Effectiveness
PDM	Product Data Management
PLM	Product Lifecycle Management
POM	Production and Operations Management
PPC	Production Planning and Control
RFID	Radio Frequency Identification
ROP	Reorder Point System
ROI	Return on Investment
RCCP	Rough Cut Capacity Planning
SA	Simulated Annealing
SMED	Single Minute Setup Die
SME	Society of Manufacturing Engineers
SKU	Stock Keeping Unit
SCM	Supply Chain Management
SD	System Dynamics
TOC	Theory of Constraints
TLA	Three Letter Acronym
TH	Throughput
TPM	Total Productive Maintenance
TQM	Total Quality Management
TPS	Toyota Production System
VDI	Verein Deutscher Ingenieure

WSAN	Wireless Sensor and Actuator Network
WIP	Work in Process

Evaluation Model

2P, 4P, 8P	Part Range (2, 4, 8 different parts)
SM, DM	Demand Mix (static, dynamic mix)
NC, FC, MC	possible Changes in Forecast (no, few, many changes)
ZV, SV	Supply Variability (zero, supply variability with ST and MTTR)
ST0.5, ST1, ST2	Setup Time (0.5, 1, 2 hours)
MTTR1, MTTR4	Mean Time to Repair (1, 4 hours)
LT4, LT12	Lead Time (4, 12 hours)
HQ, MQ, PQ	Internal Information Quality (high, medium, poor information quality)
PC1, PC24, PC120	Internal Information Availability (1, 24, 120 hours planning cycle)

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Appendix

A1. Input Data of Planning Example

		Demand			
Timestep		PartA	PartB	PartC	PartD
Day 1	00:00		60		
	01:00			60	
	02:00				60
	03:00			60	
	04:00		60		
	05:00			60	
	06:00				60
	07:00				60
	08:00				60
	09:00		60		
	10:00				60
	11:00				60
	12:00				60
	13:00				60
	14:00			60	
	15:00				60
	16:00	60			
	17:00				60
	18:00	60			
	19:00			60	
	20:00		60		
	21:00			60	
	22:00			60	
	23:00				60
Day 2	00:00		60		
	01:00	60			
	02:00	60			
	03:00	60			
	04:00		60		
	05:00		60		
	06:00		60		
	07:00		60		
	08:00	60			
	09:00		60		
	10:00			60	
	11:00			60	
	12:00			60	
	13:00				60
	14:00		60		
	15:00			60	
	16:00				60
	17:00				60
	18:00		60		
	19:00	60			
	20:00			60	
	21:00				60
	22:00	60			
	23:00	60			
Day 3	00:00			60	
	01:00				60
	02:00			60	
	03:00	60			
	04:00				60
	05:00		60		
	06:00				60
	07:00	60			
	08:00			60	
	09:00	60			
	10:00			60	
	11:00	60			
	12:00	60			
	13:00		60		
	14:00		60		
	15:00				60
	16:00		60		
	17:00		60		
	18:00				60
	19:00		60		
	20:00		60		
	21:00				60
	22:00			60	
	23:00				60
Day 4	00:00				60
	01:00	60			
	02:00				60
	03:00		60		
	04:00				60
	05:00		60		
	06:00		60		
	07:00				60
	08:00	60			
	09:00		60		
	10:00		60		
	11:00			60	
	12:00				60
	13:00	60			
	14:00		60		
	15:00				60
	16:00				60
	17:00	60			
	18:00				60
	19:00			60	
	20:00	60			
	21:00		60		
	22:00	60			
	23:00	60			
Day 5	00:00				60
	01:00	60			
	02:00	60			
	03:00				60
	04:00			60	
	05:00	60			
	06:00	60			
	07:00		60		
	08:00	60			
	09:00				60
	10:00			60	
	11:00		60		
	12:00	60			
	13:00			60	
	14:00		60		
	15:00	60			
	16:00				60
	17:00			60	
	18:00		60		
	19:00	60			
	20:00		60		
	21:00			60	
	22:00				60
	23:00				60

Initial Stock			
PartA	PartB	PartC	PartD
660	420	540	120

A2. Evaluation Results of ZV Scenarios[94]

A2.1 Kanban Results LT4[95]

	2P SM		4P SM		4P DM		8P SM	
	Setups		Setups		Setups		Setups	
WIP	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,667	4,345	0,0891	-	-	-	-	-	-
1,334	2,419	0,0470	5,634	0,0377	-	-	-	-
2,000	1,682	0,0271	3,869	0,0225	-	-	-	-
2,667	1,306	0,0318	2,924	0,0173	-	-	-	-
3,334	1,069	0,0189	2,363	0,0122	2,225	0,0293	4,770	0,0101
4,000	0,890	0,0182	1,970	0,0107	1,874	0,0241	3,981	0,0104
4,667	0,779	0,0180	1,686	0,0140	1,624	0,0113	3,419	0,0079
5,334	0,675	0,0127	1,479	0,0104	1,411	0,0353	2,997	0,0035
6,000	0,615	0,0127	1,315	0,0084	1,257	0,0175	2,664	0,0060
6,667	0,550	0,0139	1,193	0,0068	1,143	0,0179	2,395	0,0038
7,334	0,486	0,0166	1,082	0,0030	1,038	0,0146	2,179	0,0023
8,000	0,457	0,0101	0,994	0,0037	0,949	0,0156	1,996	0,0037
8,667	0,426	0,0140	0,917	0,0035	0,876	0,0169	1,850	0,0000
9,334	0,398	0,0106	0,860	0,0035	0,822	0,0157	1,709	0,0023
10,000	0,366	0,0140	0,797	0,0035	0,773	0,0117	1,600	0,0000

A2.2 Small Bucket MRP Results (LT4, NC, HQ, PC24)[96]

	2P SM		4P SM		4P DM		8P SM	
	Setups		Setups		Setups		Setups	
WIP	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,334	3,000	0,0372	8,806	0,1591	6,560	0,1152	13,882	0,1765
0,500	1,486	0,0304	4,998	0,1089	3,738	0,0871	8,606	0,1224
0,667	0,994	0,0158	3,118	0,0660	2,432	0,0569	5,940	0,0818
0,834	0,742	0,0093	2,398	0,0365	1,884	0,0480	4,998	0,0743
1,000	0,600	0,0146	2,010	0,0521	1,606	0,0224	4,284	0,0866
1,167	0,500	0,0084	1,712	0,0200	1,350	0,0787	3,542	0,0643
1,334	0,430	0,0089	1,448	0,0305	1,140	0,0404	3,122	0,0402
1,667	0,332	0,0065	1,154	0,0231	0,922	0,0415	2,546	0,0513
2,000	0,274	0,0061	0,934	0,0207	0,792	0,0606	2,120	0,0575
2,334	0,234	0,0061	0,832	0,0217	0,672	0,0268	1,918	0,0340
2,667	0,200	0,0000	0,732	0,0160	0,604	0,0320	1,700	0,0499
3,000	0,176	0,0053	0,640	0,0239	0,544	0,0341	1,518	0,0598
3,500	0,148	0,0065	0,572	0,0190	0,472	0,0171	1,354	0,0327
4,000	0,128	0,0065	0,502	0,0163	0,422	0,0173	1,176	0,0484
4,500	0,120	0,0000	0,436	0,0131	0,410	0,0397	1,128	0,0396
5,000	0,100	0,0000	0,390	0,0149	0,358	0,0249	1,002	0,0276
6,000	0,080	0,0000	0,318	0,0093	0,290	0,0161	0,868	0,0275
8,000	0,060	0,0000	0,268	0,0107	0,260	0,0253	0,738	0,0276
10,000	0,050	0,0000	0,214	0,0134	0,200	0,0207	0,706	0,0272

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[94] with WIP in days, setups in 1/day, lot size in pieces, cycle stock in days, safety stock in days.

[95] Evaluation period of 100 days with 10 seeds.

[96] Evaluation period of 50 days with 10 seeds.

A2.3 Big Bucket MRP Results (LT4, NC, HQ, PC24)[97]

	2P SM			4P SM			4P DM			8P SM		
	Lot size	Setups		Lot size	Setups		Lot size	Setups		Lot size	Setups	
WIP		Mean	95% CI		Mean	95% CI		Mean	95% CI		Mean	95% CI
1,083	540	1,804	0,06325	-	-	-	-	-	-	-	-	-
1,166	600	1,492	0,13914	-	-	-	-	-	-	-	-	-
1,334	1020	1,062	0,05060	240	3,700	0,07589	240	3,095	0,0253	-	-	-
1,667	1680	0,698	0,02530	480	2,538	0,15179	480	2,522	0,0253	180	5,652	0,37947
2,000	2160	0,560	0,03795	660	1,852	0,13914	660	1,998	0,0253	300	4,014	0,13914
2,334	2640	0,452	0,02530	900	1,432	0,07589	900	1,472	0,0253	420	3,116	0,16444
2,667	2820	0,440	0,01265	1080	1,192	0,03795	1080	1,200	0,0253	480	2,648	0,13914
3,000	-	-	-	1200	1,086	0,03795	1200	1,111	0,0253	540	2,384	0,11384
3,334	-	-	-	1500	0,926	0,01265	1500	0,911	0,0253	660	2,004	0,08854
3,667	-	-	-	1620	0,836	0,02530	1620	0,859	0,0126	780	1,780	0,05060
4,000	-	-	-	1740	0,766	0,02530	1740	0,781	0,0253	780	1,734	0,06325
4,334	-	-	-	1980	0,712	0,01265	1980	0,689	0,0126	840	1,538	0,06325
4,667	-	-	-	2160	0,642	0,01265	2160	0,639	0,0126	900	1,424	0,05060
5,000	-	-	-	2220	0,614	0,01265	2220	0,608	0,0126	960	1,382	0,06325
5,334	-	-	-	2460	0,580	0,02530	2460	0,581	0,0126	1080	1,230	0,03795
5,667	-	-	-	2640	0,522	0,01265	2640	0,521	0,0126	1140	1,180	0,03795
6,000	-	-	-	2760	0,510	0,01265	2760	0,510	0,0126	1140	1,176	0,05060
8,000	-	-	-	-	-	-	-	-	-	1560	0,828	0,03795
10,000	-	-	-	-	-	-	-	-	-	1740	0,768	0,02530

A2.4 Small Bucket MRP Results (4P SM, HQ, PC24)[98]

	FC, LT4				FC, LT12				MC, LT4				MC LT12			
	Safety Stock		Setups		Safety Stock		Setups		Safety Stock		Setups		Safety Stock		Setups	
Cycle Stock	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,333	0,017	0,034	8,962	0,1183	-	-	-	-	0,283	0,051	9,192	0,3348	-	-	-	-
0,500	0	0	4,948	0,1421	-	-	-	-	0,217	0,051	5,232	0,1760	-	-	-	-
0,667	0	0	3,184	0,0661	0	0	8,928	0,1705	0,183	0,033	3,298	0,0307	0,488	0,088	6,646	0,3168
0,833	0	0	2,448	0,0544	0	0	4,942	0,1246	0,167	0,050	2,586	0,0446	0,383	0,051	3,798	0,0641
1,000	0	0	2,074	0,0348	0	0	3,242	0,0515	0,133	0,044	2,180	0,0292	0,293	0,043	2,662	0,0624
1,167	0	0	1,754	0,0348	0	0	2,512	0,0431	0,150	0,033	1,822	0,0360	0,266	0,054	2,050	0,0785
1,333	0	0	1,486	0,0387	0	0	2,078	0,0521	0,150	0,033	1,556	0,0309	0,231	0,074	1,780	0,1048
1,667	0	0	1,174	0,0231	0	0	1,478	0,0301	0,133	0,044	1,182	0,0173	0,231	0,074	1,250	0,0665
2,000	0	0	0,960	0,0280	0	0	1,208	0,0217	0,083	0,056	0,976	0,0347	0,229	0,052	1,012	0,0560
2,333	0	0	0,830	0,0181	0	0	0,974	0,0198	0,150	0,033	0,834	0,0158	0,216	0,051	0,840	0,0706
2,667	0	0	0,736	0,0187	0	0	0,838	0,0256	0,083	0,056	0,744	0,0297	0,216	0,051	0,734	0,0761
3,000	0	0	0,652	0,0171	0	0	0,746	0,0198	0,067	0,054	0,658	0,0219	0,166	0,000	0,600	0,0321
3,500	0	0	0,560	0,0146	0	0	0,612	0,0225	0,067	0,054	0,562	0,0139	0,216	0,051	0,554	0,0280
4,000	0	0	0,488	0,0200	0	0	0,548	0,0122	0,050	0,051	0,500	0,0169	0,166	0,050	0,492	0,0427
4,500	0	0	0,434	0,0169	0	0	0,464	0,0265	0,067	0,054	0,440	0,0179	0,149	0,060	0,408	0,0208
5,000	0	0	0,412	0,0200	0	0	0,430	0,0217	0,017	0,033	0,392	0,0171	0,149	0,060	0,400	0,0348
6,000	0	0	0,360	0,0158	0	0	0,370	0,0089	0,033	0,044	0,340	0,0231	0,116	0,051	0,318	0,0324
8,000	0	0	0,284	0,0196	0	0	0,284	0,0131	0,067	0,054	0,292	0,0190	0,216	0,100	0,292	0,0401
10,000	0	0	0,238	0,0173	0	0	0,240	0,0246	0,017	0,033	0,232	0,0171	0,129	0,044	0,158	0,0126

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[97] Evaluation period of 25 days with 20 seeds.

[98] Evaluation period of 50 days with 10 seeds.

A2.5 Small Bucket MRP Results (4P SM, HQ, LT4)[99]

	MC, PC1		FC, PC120				MC, PC120			
	Safety Stock	Setups	Safety Stock		Setups		Safety Stock		Setups	
Cycle Stock	*(only one experiment)*		Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,333	0,167	8,840	1,833	0,3063	5,026	0,2420	2,717	0,4129	4,580	0,2336
0,500	0,167	4,840	1,550	0,3222	3,610	0,2257	2,467	0,3576	3,396	0,1909
0,667	0,000	3,520	1,467	0,2572	2,862	0,0694	2,400	0,3624	2,664	0,0793
0,833	0,000	2,480	1,483	0,3275	2,362	0,0576	2,050	0,2536	2,334	0,0881
1,000	0,167	2,160	1,233	0,1507	2,058	0,0913	2,133	0,2620	1,924	0,0817
1,167	0,000	1,680	1,183	0,1528	1,678	0,0389	1,867	0,1975	1,708	0,0867
1,333	0,000	1,400	1,167	0,2331	1,476	0,0487	1,800	0,3326	1,470	0,0557
1,667	0,000	1,120	1,250	0,2865	1,204	0,0552	1,600	0,1736	1,186	0,0353
2,000	0,000	0,960	1,200	0,4603	0,990	0,0300	1,517	0,1822	1,002	0,0375
2,333	0,000	0,920	0,800	0,1296	0,858	0,0398	1,417	0,2180	0,864	0,0155
2,667	0,000	0,800	0,917	0,2497	0,760	0,0321	1,283	0,3851	0,762	0,0365
3,000	0,167	0,600	0,850	0,1681	0,668	0,0349	1,600	0,4422	0,668	0,0247
3,500	0,000	0,560	0,883	0,1863	0,576	0,0272	1,250	0,1809	0,594	0,0292
4,000	0,000	0,480	0,767	0,1237	0,514	0,0169	1,433	0,3556	0,520	0,0363
4,500	0,000	0,440	0,850	0,1822	0,454	0,0280	1,217	0,1991	0,446	0,0169
5,000	0,000	0,360	0,750	0,1940	0,474	0,0438	1,417	0,3660	0,456	0,0362
6,000	0,000	0,360	0,750	0,1242	0,386	0,0147	0,950	0,2536	0,368	0,0268
8,000	0,000	0,240	0,817	0,1160	0,258	0,0139	1,150	0,3238	0,296	0,0314
10,000	0,000	0,240	0,633	0,1633	0,248	0,0254	1,017	0,3000	0,294	0,0260

A2.6 Big Bucket MRP Results (4P SM, HQ, LT4)[100]

	FC, PC120				MC, PC120			
	Safety Stock		Setups		Safety Stock		Setups	
Cycle Stock	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
1,334	0,758	0,2143	3,848	0,0759	1,208	0,2688	3,860	0,0759
1,667	0,550	0,2214	2,774	0,0506	0,983	0,2126	2,782	0,0506
2,000	0,433	0,1950	2,072	0,0506	0,867	0,3250	2,030	0,0506
2,334	0,333	0,2055	1,512	0,0253	0,858	0,3320	1,494	0,0253
2,667	0,242	0,1300	1,300	0,0253	0,608	0,2319	1,292	0,0253
3,000	0,342	0,2653	1,124	0,0253	0,483	0,2776	1,122	0,0253
3,334	0,292	0,1669	0,904	0,0253	0,475	0,2196	0,904	0,0253
3,667	0,225	0,1388	0,858	0,0253	0,450	0,2372	0,850	0,0253
4,000	0,233	0,2091	0,784	0,0253	0,308	0,2091	0,786	0,0253
4,334	0,225	0,1195	0,702	0,0253	0,433	0,2091	0,698	0,0253
4,667	0,300	0,2161	0,634	0,0000	0,425	0,2688	0,618	0,0253
5,000	0,225	0,1915	0,618	0,0253	0,300	0,2424	0,622	0,0253
5,334	0,308	0,2284	0,546	0,0253	0,442	0,2319	0,548	0,0253
5,667	0,400	0,2301	0,508	0,0253	0,450	0,2161	0,506	0,0253
6,000	0,467	0,3970	0,504	0,0253	0,358	0,2178	0,506	0,0253

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[99] Evaluation period of 50 days with 10 seeds except in 60mins scenario only one seed due to the long running time.

[100] Evaluation period of 25 days with 20 seeds.

A2.7 Small Bucket MRP Results (4P SM, NC, LT4, PC24)[101]

	MQ				PQ			
	Safety Stock		Setups		Safety Stock		Setups	
Cycle Stock	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,333	0,033	0,0444	11,130	0,4111	0,467	0,1296	9,366	0,6908
0,500	0,100	0,0544	6,304	0,2381	0,533	0,1197	6,166	0,3776
0,667	0,117	0,0509	3,976	0,1340	0,517	0,1262	4,474	0,2509
0,833	0,167	0,0497	2,958	0,0805	0,517	0,0778	3,414	0,2286
1,000	0,133	0,0444	2,350	0,0470	0,550	0,1000	2,788	0,1238
1,167	0,150	0,0333	1,938	0,0482	0,550	0,0868	2,262	0,0911
1,333	0,133	0,0667	1,688	0,0359	0,517	0,0923	1,892	0,0778
1,667	0,150	0,0333	1,284	0,0352	0,400	0,1133	1,494	0,0733
2,000	0,100	0,0544	1,042	0,0234	0,367	0,0667	1,196	0,0441
2,333	0,133	0,0667	0,888	0,0268	0,350	0,1048	1,022	0,0379
2,667	0,100	0,0544	0,788	0,0136	0,330	0,1018	0,902	0,0432
3,000	0,133	0,0444	0,690	0,0209	0,267	0,0737	0,746	0,0286
3,500	0,083	0,0556	0,582	0,0151	0,300	0,0667	0,630	0,0240
4,000	0,083	0,0745	0,530	0,0137	0,217	0,0868	0,564	0,0196
4,500	0,050	0,0509	0,466	0,0207	0,233	0,1018	0,508	0,0240
5,000	0,067	0,0544	0,400	0,0084	0,250	0,0556	0,442	0,0256
6,000	0,000	0,0000	0,356	0,0131	0,233	0,0889	0,362	0,0219
8,000	0,050	0,0509	0,278	0,0139	0,267	0,1018	0,288	0,0200
10,000	0,067	0,0544	0,246	0,0158	0,150	0,1048	0,244	0,0080

A2.8 Big Bucket MRP Results (4P SM, NC, LT4, PC24)[102]

	MQ				PQ			
	Safety Stock		Setups		Safety Stock		Setups	
Cycle Stock	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
1,334	0,083	0,0632	3,293	0,0379	0,350	0,1072	3,435	0,0759
1,667	0,100	0,0861	2,468	0,0253	0,283	0,1335	2,355	0,0379
2,000	0,050	0,0597	1,939	0,0506	0,433	0,2477	1,788	0,0632
2,334	0,108	0,1335	1,432	0,0253	0,450	0,1810	1,343	0,0506
2,667	0,025	0,0509	1,179	0,0253	0,283	0,2424	1,148	0,0253
3,000	0,050	0,0966	1,085	0,0253	0,283	0,2319	1,047	0,0379
3,334	0,042	0,0826	0,876	0,0126	0,508	0,3092	0,843	0,0253
3,667	0,008	0,0228	0,822	0,0253	0,475	0,3883	0,793	0,0253
4,000	0,025	0,0703	0,763	0,0126	0,442	0,4691	0,743	0,0253
4,334	0,067	0,0861	0,663	0,0126	0,358	0,3707	0,656	0,0126
4,667	0,075	0,0878	0,625	0,0126	0,242	0,1388	0,601	0,0253
5,000	0,017	0,0474	0,597	0,0126	0,167	0,1564	0,595	0,0126
5,334	0,033	0,0738	0,545	0,0126	0,358	0,3479	0,538	0,0126
5,667	0,042	0,0474	0,510	0,0126	0,367	0,2793	0,498	0,0126
6,000	0,025	0,0509	0,493	0,0126	0,208	0,2881	0,479	0,0126

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[101] Evaluation period of 50 days with 10 seeds.

[102] Evaluation period of 25 days with 20 seeds.

A2.9 Small Bucket MRP Results (2P SM, MC)[103]

	MQ, LT4, PC24				PQ, LT12, PC24				MQ, LT4, PC120				PQ, LT12, PC120			
	Safety Stock		Setups		Safety Stock		Setups		Safety Stock		Setups		Safety Stock		Setups	
Cycle Stock	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,333	0,092	0,0167	4,132	0,1849	0,608	0,0788	9,440	0,7752	1,183	0,2731	2,718	0,3144	1,742	0,2859	6,250	1,1778
0,500	0,117	0,0369	1,736	0,0572	0,700	0,1343	6,420	0,6499	1,000	0,2422	1,432	0,0918	1,583	0,2733	5,410	0,7843
0,667	0,175	0,0389	1,114	0,0130	0,717	0,1144	4,026	0,3586	0,875	0,1454	1,000	0,0711	1,425	0,2158	4,064	0,9861
0,833	0,150	0,0333	0,802	0,0117	0,692	0,0931	2,694	0,3190	0,842	0,1415	0,796	0,0265	1,467	0,3851	2,656	0,7193
1,000	0,150	0,0333	0,638	0,0174	0,617	0,1117	1,744	0,2315	0,917	0,2108	0,592	0,0261	1,433	0,3919	1,700	0,4512
1,167	0,133	0,0444	0,528	0,0186	0,583	0,0657	1,198	0,1303	0,758	0,1348	0,528	0,0148	1,542	0,5020	1,388	0,5268
1,333	0,125	0,0373	0,444	0,0125	0,492	0,0764	0,850	0,1248	0,708	0,1557	0,438	0,0210	1,583	0,3952	0,950	0,2661
1,667	0,150	0,0416	0,348	0,0111	0,417	0,0786	0,530	0,0318	0,667	0,0962	0,350	0,0123	1,825	0,5302	0,612	0,2822
2,000	0,142	0,0434	0,282	0,0090	0,492	0,1500	0,394	0,0236	0,733	0,1736	0,280	0,0133	1,500	0,4574	0,444	0,0371
2,333	0,092	0,0389	0,242	0,0050	0,492	0,1008	0,330	0,0201	0,683	0,2046	0,242	0,0111	1,675	0,6486	0,348	0,0247
2,667	0,083	0,0351	0,204	0,0100	0,392	0,1292	0,258	0,0117	0,450	0,1670	0,210	0,0067	1,708	0,6311	0,272	0,0275
3,000	0,092	0,0524	0,180	0,0000	0,400	0,1133	0,228	0,0133	0,725	0,2898	0,180	0,0060	1,650	0,5962	0,238	0,0324
3,500	0,075	0,0461	0,154	0,0076	0,317	0,1212	0,200	0,0167	0,783	0,2386	0,154	0,0061	1,525	0,4403	0,190	0,0200
4,000	0,083	0,0351	0,136	0,0067	0,375	0,1090	0,204	0,0884	0,650	0,2120	0,130	0,0067	1,375	0,3045	0,154	0,0134
4,500	0,042	0,0278	0,120	0,0000	0,300	0,1575	0,142	0,0050	0,583	0,2950	0,116	0,0053	1,292	0,3125	0,132	0,0088
5,000	0,050	0,0272	0,100	0,0000	0,233	0,0889	0,116	0,0067	0,542	0,2082	0,102	0,0040	1,200	0,7185	0,118	0,0093
6,000	0,033	0,0272	0,082	0,0050	0,233	0,1048	0,100	0,0000	0,200	0,0969	0,086	0,0061	0,950	0,6695	0,096	0,0100
8,000	0,017	0,0222	0,060	0,0000	0,142	0,1026	0,080	0,0105	0,300	0,1614	0,062	0,0040	0,600	0,4680	0,068	0,0065
10,000	0,008	0,0167	0,052	0,0082	0,125	0,1118	0,060	0,0000	0,292	0,1726	0,058	0,0040	0,725	0,8123	0,058	0,0040

A2.10 Small Bucket MRP Results (4P SM, MC)[104]

	MQ, LT4, PC24				PQ, LT12, PC24				MQ, LT4, PC120				PQ, LT12, PC120			
	Safety Stock		Setups		Safety Stock		Setups		Safety Stock		Setups		Safety Stock		Setups	
Cycle Stock	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,333	0,283	0,0711	11,110	0,3127	1,017	0,1822	13,248	0,7241	2,617	0,3753	4,636	0,4292	3,233	0,3855	5,770	1,0956
0,500	0,233	0,0737	6,414	0,1484	1,033	0,2037	10,386	0,7255	2,383	0,4333	3,824	0,3602	3,433	0,5735	5,144	1,0402
0,667	0,200	0,0444	4,096	0,0918	0,950	0,1928	8,084	0,4592	2,150	0,1953	2,980	0,1498	3,467	0,9911	4,116	0,7516
0,833	0,250	0,0556	3,048	0,0489	0,933	0,1333	5,954	0,3060	2,267	0,2906	2,544	0,1492	3,450	0,8059	3,246	0,4339
1,000	0,217	0,0868	2,460	0,0520	0,783	0,0868	4,582	0,3156	1,967	0,3471	2,132	0,1265	3,500	1,0074	2,832	0,3627
1,167	0,200	0,0667	1,996	0,0574	0,833	0,2383	3,612	0,1289	1,850	0,1889	1,852	0,0899	3,300	0,8341	2,542	0,4390
1,333	0,183	0,0598	1,714	0,0723	0,633	0,0667	2,896	0,1594	1,883	0,1495	1,622	0,0907	2,967	0,7647	2,240	0,2649
1,667	0,167	0,0000	1,328	0,0410	0,633	0,0969	2,076	0,0914	1,600	0,1018	1,272	0,0534	3,000	0,8135	1,822	0,3860
2,000	0,167	0,0703	1,086	0,0353	0,583	0,1024	1,600	0,0747	1,533	0,2096	1,056	0,0484	2,850	0,5868	1,376	0,1659
2,333	0,183	0,1160	0,900	0,0231	0,583	0,1024	1,276	0,0751	1,550	0,1991	0,934	0,0413	2,767	0,3031	1,176	0,1142
2,667	0,150	0,0598	0,754	0,0327	0,550	0,1000	1,098	0,0531	1,633	0,2320	0,784	0,0177	2,483	0,4955	0,936	0,0797
3,000	0,167	0,0497	0,686	0,0198	0,483	0,1160	0,920	0,0337	1,517	0,3599	0,702	0,0475	2,400	0,4073	0,892	0,0736
3,500	0,117	0,0711	0,574	0,0189	0,617	0,1410	0,764	0,0495	1,450	0,2813	0,582	0,0350	2,433	0,5515	0,816	0,1330
4,000	0,067	0,0544	0,506	0,0207	0,367	0,0969	0,636	0,0320	1,233	0,2592	0,536	0,0341	2,383	0,5044	0,702	0,0897
4,500	0,100	0,0544	0,474	0,0246	0,367	0,0667	0,536	0,0272	1,733	0,4012	0,506	0,0553	2,033	0,4031	0,592	0,0503
5,000	0,067	0,0544	0,408	0,0208	0,500	0,1111	0,498	0,0411	1,450	0,3687	0,500	0,0382	1,933	0,3692	0,534	0,0405
6,000	0,050	0,0509	0,330	0,0161	0,417	0,1242	0,404	0,0399	1,183	0,2076	0,400	0,0321	1,800	0,4813	0,478	0,0515
8,000	0,067	0,0544	0,268	0,0148	0,333	0,0994	0,278	0,0111	1,000	0,2629	0,250	0,0123	1,833	0,2811	0,310	0,0240
10,000	0,067	0,0544	0,218	0,0151	0,283	0,1495	0,268	0,0268	1,217	0,3222	0,274	0,0260	1,500	0,2854	0,286	0,0547

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[103] Evaluation period of 50 days with 10 seeds.

[104] Evaluation period of 50 days with 10 seeds.

A2.11 Small Bucket MRP Results (8P SM, MC)[105]

	MQ, LT4, PC24				PQ, LT12, PC24				MQ, LT4, PC120				PQ, LT12, PC120			
	Safety Stock		Setups		Safety Stock		Setups		Safety Stock		Setups		Safety Stock		Setups	
Cycle Stock	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,333	0,733	0,1333	15,442	0,5280	1,900	0,3304	14,960	0,5476	4,867	0,5087	6,624	0,3058	5,367	0,4709	6,580	0,4991
0,500	0,533	0,1089	11,594	0,2356	1,700	0,2096	13,188	0,4636	4,633	0,5301	6,050	0,2437	5,067	0,4949	6,328	0,3448
0,667	0,467	0,1089	8,538	0,1546	1,500	0,2049	11,530	0,2717	4,467	0,3326	5,276	0,2186	5,200	0,3611	5,568	0,4336
0,833	0,367	0,0667	6,506	0,1298	1,267	0,1333	10,026	0,4125	4,100	0,4338	4,608	0,1946	5,033	0,4151	4,850	0,3946
1,000	0,400	0,0889	5,614	0,0978	1,067	0,1333	8,504	0,3048	4,333	0,3443	4,280	0,1832	5,000	0,5164	4,590	0,2819
1,167	0,367	0,0667	4,760	0,1052	1,000	0,1988	7,244	0,2572	3,800	0,3745	3,782	0,1679	5,000	0,5259	4,292	0,3682
1,333	0,367	0,0667	4,028	0,0860	1,100	0,1423	6,130	0,1466	3,533	0,3174	3,400	0,0764	4,867	0,4576	3,892	0,1621
1,667	0,333	0,0000	3,088	0,0691	0,933	0,1663	4,708	0,1241	3,367	0,4269	2,854	0,0924	4,367	0,3645	3,496	0,2249
2,000	0,300	0,0667	2,540	0,0839	0,800	0,1474	3,780	0,1641	3,033	0,4151	2,486	0,0768	4,133	0,4467	2,842	0,2300
2,333	0,267	0,1333	2,212	0,0626	0,733	0,0889	3,074	0,1416	2,967	0,4914	2,124	0,1013	4,033	0,3645	2,642	0,1414
2,667	0,233	0,1018	1,894	0,0569	0,833	0,2049	2,594	0,1103	2,833	0,3333	1,902	0,0823	3,867	0,4467	2,400	0,1511
3,000	0,200	0,1089	1,720	0,0343	0,767	0,1018	2,146	0,1007	2,567	0,3981	1,698	0,0493	3,900	0,4974	2,078	0,0936
3,500	0,300	0,0667	1,478	0,0436	0,767	0,2000	1,884	0,0763	2,667	0,3296	1,436	0,0395	3,867	0,4000	1,842	0,1271
4,000	0,200	0,1089	1,284	0,0622	0,667	0,1018	1,658	0,1284	2,533	0,1474	1,312	0,0597	3,433	0,3304	1,630	0,1637
4,500	0,200	0,1089	1,174	0,0656	0,667	0,1405	1,394	0,0623	2,333	0,2434	1,230	0,0606	3,067	0,2776	1,567	0,0825
5,000	0,167	0,1111	1,096	0,0802	0,633	0,0667	1,244	0,0625	2,467	0,4240	1,248	0,1421	3,433	0,5626	1,366	0,1167
6,000	0,167	0,1111	0,936	0,0687	0,533	0,1474	1,062	0,0504	2,433	0,3450	1,054	0,1096	3,100	0,3855	1,218	0,1797
8,000	0,067	0,0889	0,778	0,0673	0,467	0,1474	0,812	0,0686	2,033	0,4269	0,810	0,0410	3,100	0,7440	0,884	0,0390
10,000	0,100	0,1018	0,700	0,0690	0,600	0,1333	0,702	0,0982	2,067	0,4848	0,708	0,0907	2,567	0,5169	0,794	0,1248

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[105] Evaluation period of 50 days with 10 seeds.

A3. Evaluation Results of SV Scenarios[106]

A3.1 Kanban Results (4P SM, ST30, MTTR1)

Container		WIP		Service Level		Setups		Working		Setting-up		Idle		Failed	
Amount	Size	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
8	300	0,912	0,0283	94,52%	0,487%	4,381	0,0353	82,63%	0,441%	9,13%	0,073%	0,00%	0,000%	8,24%	0,497%
8	360	1,097	0,0439	96,04%	0,521%	3,744	0,0272	83,89%	0,464%	7,80%	0,057%	0,00%	0,000%	8,31%	0,496%
8	420	1,273	0,0552	97,21%	0,570%	3,234	0,0169	84,96%	0,466%	6,74%	0,035%	0,00%	0,000%	8,31%	0,496%
8	480	1,515	0,0677	98,21%	0,474%	2,877	0,0270	85,70%	0,457%	5,99%	0,058%	0,00%	0,000%	8,31%	0,496%
8	540	1,778	0,1379	98,91%	0,476%	2,582	0,0181	86,31%	0,474%	5,38%	0,038%	0,00%	0,000%	8,31%	0,496%
8	600	2,162	0,2497	99,54%	0,337%	2,340	0,0162	86,82%	0,484%	4,87%	0,035%	0,00%	0,000%	8,31%	0,496%
8	660	2,835	0,4090	99,87%	0,187%	2,137	0,0202	87,21%	0,487%	4,45%	0,042%	0,03%	0,050%	8,31%	0,496%
8	720	3,628	0,3643	99,99%	0,028%	1,969	0,0160	87,43%	0,490%	4,10%	0,033%	0,16%	0,118%	8,31%	0,496%
8	780	4,356	0,1541	100,0%	0,000%	1,820	0,0143	87,33%	0,411%	3,79%	0,029%	0,57%	0,240%	8,31%	0,496%
8	840	4,814	0,0927	100,0%	0,000%	1,693	0,0147	87,24%	0,298%	3,53%	0,030%	0,93%	0,268%	8,31%	0,496%
8	900	5,237	0,0980	100,0%	0,000%	1,576	0,0069	87,25%	0,294%	3,28%	0,014%	1,16%	0,299%	8,31%	0,496%
8	960	5,607	0,0871	100,0%	0,000%	1,490	0,0048	87,35%	0,290%	3,10%	0,010%	1,24%	0,312%	8,31%	0,496%
8	1020	5,983	0,0754	100,0%	0,000%	1,402	0,0066	87,31%	0,277%	2,92%	0,013%	1,47%	0,277%	8,31%	0,496%

A3.2 Small Bucket MRP Results (4P SM, ST30, MTTR1)

	Cycle Stock 1,333 (32h)						Cycle Stock 1,416 (34h)						Cycle Stock 1,500 (36h)					
	WIP		Service Level		Setups		WIP		Service Level		Setups		WIP		Service Level		Setups	
Safety Stock	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,000	1,394	0,0055	96,06%	0,225%	1,673	0,0643	1,477	0,0068	96,09%	0,285%	1,613	0,0703	1,585	0,0062	96,26%	0,241%	1,489	0,0496
0,166	1,484	0,0152	98,51%	0,317%	1,807	0,0878	1,571	0,0173	98,72%	0,250%	1,691	0,0688	1,669	0,0119	98,76%	0,243%	1,614	0,0653
0,333	1,586	0,0250	99,37%	0,198%	1,881	0,0812	1,680	0,0230	99,22%	0,159%	1,809	0,0683	1,774	0,0237	99,41%	0,155%	1,689	0,0798
0,667	1,868	0,0275	99,70%	0,137%	1,895	0,1063	1,963	0,0301	99,67%	0,171%	1,771	0,0585	2,075	0,0263	99,80%	0,116%	1,699	0,0473
1,000	2,171	0,0564	99,83%	0,111%	1,898	0,0942	2,259	0,0547	99,83%	0,126%	1,791	0,0646	2,393	0,0407	99,92%	0,076%	1,660	0,0970
1,333	2,468	0,0875	99,89%	0,100%	1,951	0,1248	2,580	0,0517	99,92%	0,089%	1,777	0,0877	2,717	0,0410	99,97%	0,034%	1,659	0,0824
1,667	2,795	0,0862	99,96%	0,044%	1,925	0,1139	2,885	0,0803	99,95%	0,087%	1,813	0,0806	3,047	0,0434	99,99%	0,018%	1,670	0,0915
2,000	3,106	0,1113	100,0%	0,006%	1,941	0,1292	3,225	0,0685	99,99%	0,012%	1,781	0,0898	3,381	0,0435	100,0%	0,000%	1,667	0,0892
2,333	3,451	0,0959	100,0%	0,000%	1,922	0,1059	3,558	0,0690	99,99%	0,013%	1,793	0,0787	3,714	0,0435	100,0%	0,000%	1,667	0,0892
2,667	3,785	0,0959	100,0%	0,000%	1,922	0,1059	3,891	0,0693	100,0%	0,000%	1,784	0,0864	4,047	0,0435	100,0%	0,000%	1,667	0,0892

A3.3 Kanban Results (4P SM, ST0.5)

		MTTR1						MTTR4					
Container		WIP		Service Level		Setups		WIP		Service Level		Setups	
Amount	Size	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
8	300	0,912	0,0283	94,52%	0,487%	4,381	0,0353	0,933	0,0729	93,28%	1,734%	4,321	0,0830
8	360	1,097	0,0439	96,04%	0,521%	3,744	0,0272	1,158	0,0885	95,75%	1,150%	3,726	0,0327
8	420	1,273	0,0552	97,21%	0,570%	3,234	0,0169	1,391	0,1540	96,89%	1,168%	3,239	0,0227
8	480	1,515	0,0677	98,21%	0,474%	2,877	0,0270	1,665	0,1906	97,85%	1,118%	2,870	0,0357
8	540	1,778	0,1379	98,91%	0,476%	2,582	0,0181	2,027	0,3657	98,50%	0,957%	2,573	0,0270
8	600	2,162	0,2497	99,54%	0,337%	2,340	0,0162	2,402	0,4469	98,99%	0,848%	2,330	0,0282
8	660	2,835	0,4090	99,87%	0,187%	2,137	0,0202	2,751	0,4832	99,38%	0,636%	2,126	0,0194
8	720	3,628	0,3643	99,99%	0,028%	1,969	0,0160	3,198	0,5330	99,70%	0,351%	1,964	0,0188
8	780	4,356	0,1541	100,00%	0,000%	1,820	0,0143	3,654	0,5119	99,81%	0,234%	1,802	0,0231
8	840	-	-	-	-	-	-	4,154	0,5275	99,95%	0,085%	1,676	0,0248
8	900	-	-	-	-	-	-	4,593	0,5029	99,95%	0,086%	1,580	0,0185
8	960	-	-	-	-	-	-	5,040	0,4570	99,99%	0,028%	1,477	0,0090
8	1020	-	-	-	-	-	-	5,493	0,4212	100,0%	0,000%	1,394	0,0118

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[106] using the settings MC, LT4, HQ, PC24 with WIP in days, service level in %, setups in 1/day, container size in pieces per container, container amount in number of cards, machine status (working, setting-up, idle, failed) in %. All Results with an evaluation period of 100 days with 10 seeds.

A3.4 Kanban Results (4P SM, ST1)

		MTTR1						MTTR4					
Container		WIP		Service Level		Setups		WIP		Service Level		Setups	
Amount	Size	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
8	600	1,309	0,0481	94,35%	0,527%	2,236	0,0123	1,350	0,0871	94,09%	1,109%	2,227	0,0309
8	660	1,470	0,0568	95,26%	0,474%	2,046	0,0090	1,514	0,1040	94,88%	1,133%	2,048	0,0259
8	720	1,614	0,0566	95,92%	0,546%	1,892	0,0125	1,656	0,1431	95,54%	1,064%	1,897	0,0286
8	780	1,769	0,0969	96,59%	0,516%	1,762	0,0088	1,840	0,1744	96,21%	1,129%	1,757	0,0216
8	840	1,924	0,1047	97,13%	0,465%	1,648	0,0100	2,037	0,1910	96,83%	1,159%	1,643	0,0246
8	900	2,118	0,1199	97,66%	0,423%	1,542	0,0106	2,226	0,2506	97,39%	1,053%	1,548	0,0193
8	960	2,344	0,1381	97,97%	0,480%	1,458	0,0111	2,447	0,3033	97,84%	1,051%	1,450	0,0229
8	1020	2,502	0,1622	98,44%	0,351%	1,380	0,0089	2,690	0,3454	98,24%	0,986%	1,378	0,0157
8	1080	2,734	0,1460	98,68%	0,324%	1,300	0,0122	3,026	0,5067	98,64%	1,003%	1,299	0,0212
8	1140	3,007	0,1632	99,16%	0,324%	1,244	0,0108	3,535	0,7817	98,95%	0,752%	1,238	0,0106
8	1200	3,370	0,2479	99,44%	0,223%	1,175	0,0091	3,949	1,0227	99,21%	0,795%	1,173	0,0182
8	1260	3,715	0,3521	99,69%	0,232%	1,127	0,0107	4,398	1,0836	99,44%	0,550%	1,124	0,0152
8	1320	4,276	0,5124	99,85%	0,131%	1,078	0,0116	4,972	1,1495	99,69%	0,352%	1,070	0,0131
8	1380	5,549	0,9741	99,98%	0,047%	1,036	0,0060	5,609	1,1776	99,84%	0,270%	1,031	0,0149
8	1440	6,826	0,9794	100,0%	0,000%	0,995	0,0061	6,263	1,2244	99,93%	0,117%	0,996	0,0108
8	1500	-	-	-	-	-	-	6,858	1,1256	99,89%	0,127%	0,950	0,0143
8	1560	-	-	-	-	-	-	7,540	0,9853	100,0%	0,004%	0,913	0,0112

A3.5 Kanban Results (4P SM, ST2)

		MTTR1						MTTR4					
Container		WIP		Service Level		Setups		WIP		Service Level		Setups	
Amount	Size	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
8	1320	2,216	0,0882	95,15%	0,531%	1,036	0,0060	2,371	0,1860	94,88%	1,248%	1,032	0,0116
8	1440	2,526	0,1200	96,00%	0,550%	0,957	0,0059	2,630	0,2587	95,52%	1,064%	0,956	0,0113
8	1560	2,787	0,2186	96,46%	0,413%	0,885	0,0051	2,877	0,2463	96,34%	1,181%	0,887	0,0135
8	1680	3,072	0,1848	97,20%	0,418%	0,829	0,0041	3,147	0,2813	96,83%	1,214%	0,829	0,0104
8	1800	3,304	0,2318	97,44%	0,358%	0,777	0,0048	3,475	0,3297	97,34%	1,022%	0,776	0,0102
8	1920	3,581	0,1532	98,02%	0,427%	0,730	0,0058	3,782	0,3635	97,81%	0,936%	0,731	0,0114
8	2040	3,987	0,1612	98,40%	0,500%	0,692	0,0056	4,130	0,4707	98,23%	0,938%	0,693	0,0076
8	2160	4,263	0,1775	98,94%	0,287%	0,657	0,0035	4,609	0,6584	98,64%	0,722%	0,657	0,0076
8	2280	4,680	0,3636	99,22%	0,420%	0,622	0,0066	5,297	0,8194	99,00%	0,665%	0,623	0,0076
8	2400	5,187	0,2817	99,37%	0,404%	0,595	0,0038	5,865	1,1027	99,25%	0,575%	0,595	0,0070
8	2520	5,829	0,4367	99,71%	0,242%	0,565	0,0051	7,516	1,9608	99,55%	0,438%	0,569	0,0079
8	2580	6,857	0,9465	99,86%	0,157%	0,556	0,0037	8,141	2,3766	99,64%	0,367%	0,554	0,0090
8	2640	8,323	1,3697	100,0%	0,009%	0,542	0,0045	9,617	2,3306	100,0%	0,016%	0,542	0,0066

A3.6 Small Bucket MRP Results (4P SM, ST0.5)

		MTTR1						MTTR4					
Stock		WIP		Service Level		Setups		WIP		Service Level		Setups	
Cycle	Safety	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
1,4167	0,000	1,477	0,0068	96,09%	0,285%	1,613	0,0703	1,403	0,0266	96,20%	0,313%	1,723	0,0520
1,4167	0,166	1,571	0,0173	98,72%	0,250%	1,691	0,0688	1,508	0,0359	97,67%	0,231%	1,801	0,0475
1,4167	0,333	1,680	0,0230	99,22%	0,159%	1,809	0,0683	1,645	0,0240	98,62%	0,238%	1,746	0,0419
1,4167	0,667	1,963	0,0301	99,67%	0,171%	1,771	0,0585	1,921	0,0326	99,21%	0,316%	1,776	0,0831
1,4167	1,000	2,259	0,0547	99,83%	0,126%	1,791	0,0646	2,203	0,0434	99,65%	0,149%	1,767	0,0714
1,4167	1,333	2,580	0,0517	99,92%	0,089%	1,777	0,0877	2,482	0,0619	99,72%	0,145%	1,789	0,0798
1,4167	1,667	2,885	0,0803	99,95%	0,087%	1,813	0,0806	2,775	0,1038	99,77%	0,152%	1,836	0,0815
1,4167	2,000	3,225	0,0685	99,99%	0,012%	1,781	0,0898	3,088	0,1124	99,92%	0,073%	1,797	0,0759
1,4167	2,333	3,558	0,0690	99,99%	0,013%	1,793	0,0787	3,423	0,1056	99,97%	0,058%	1,767	0,0737
1,4167	2,667	3,891	0,0693	100,0%	0,000%	1,784	0,0864	3,717	0,1350	100,0%	0,009%	1,836	0,0844

A3.7 Small Bucket MRP Results (4P SM, ST1)

		MTTR1						MTTR4					
Stock		WIP		Service Level		Setups		WIP		Service Level		Setups	
Cycle	Safety	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
2,500	0,000	2,522	0,0166	96,89%	0,209%	0,954	0,0498	2,410	0,0569	97,49%	0,187%	0,960	0,0399
2,500	0,166	2,605	0,0286	98,83%	0,288%	0,965	0,0466	2,534	0,0557	98,37%	0,303%	0,980	0,0442
2,500	0,333	2,728	0,0283	99,30%	0,249%	0,990	0,0494	2,672	0,0453	98,90%	0,185%	0,994	0,0470
2,500	0,667	3,016	0,0480	99,64%	0,235%	0,950	0,0414	2,970	0,0545	99,22%	0,213%	0,989	0,0487
2,500	1,000	3,319	0,0500	99,77%	0,153%	0,960	0,0407	3,245	0,0914	99,41%	0,311%	1,039	0,0860
2,500	1,333	3,626	0,0586	99,90%	0,097%	0,961	0,0597	3,565	0,0766	99,64%	0,193%	0,988	0,0648
2,500	1,667	3,938	0,0709	99,97%	0,039%	0,959	0,0583	3,831	0,1278	99,75%	0,188%	1,032	0,0813
2,500	2,000	4,262	0,0765	99,99%	0,014%	0,964	0,0556	4,142	0,1433	99,84%	0,143%	1,020	0,0605
2,500	2,333	4,595	0,0770	100,0%	0,000%	0,965	0,0573	4,467	0,1491	99,94%	0,083%	1,014	0,0592
2,500	2,667	4,928	0,0770	100,0%	0,000%	0,965	0,0573	4,773	0,1726	99,97%	0,052%	1,022	0,0608
2,500	3,000	5,262	0,0770	100,0%	0,000%	0,965	0,0573	5,108	0,1704	100,0%	0,019%	1,011	0,0633

A3.8 Small Bucket MRP Results (4P SM, ST2)

		MTTR1						MTTR4					
Stock		WIP		Service Level		Setups		WIP		Service Level		Setups	
Cycle	Safety	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
3,9167	0,000	3,847	0,0405	97,95%	0,201%	0,522	0,0250	3,774	0,0625	97,78%	0,200%	0,526	0,0296
3,9167	0,166	3,949	0,0513	98,68%	0,240%	0,555	0,0176	3,892	0,0598	98,68%	0,255%	0,528	0,0150
3,9167	0,333	4,100	0,0269	99,30%	0,145%	0,528	0,0205	4,038	0,0594	99,10%	0,256%	0,523	0,0213
3,9167	0,667	4,386	0,0464	99,65%	0,174%	0,513	0,0122	4,340	0,0770	99,41%	0,234%	0,508	0,0252
3,9167	1,000	4,683	0,0689	99,80%	0,135%	0,516	0,0140	4,678	0,0664	99,58%	0,170%	0,503	0,0182
3,9167	1,333	4,986	0,0785	99,91%	0,064%	0,510	0,0185	4,971	0,1100	99,75%	0,149%	0,499	0,0160
3,9167	1,667	5,311	0,0922	99,97%	0,039%	0,504	0,0136	5,302	0,1100	99,87%	0,107%	0,478	0,0121
3,9167	2,000	5,637	0,1042	99,99%	0,013%	0,505	0,0127	5,582	0,1621	99,94%	0,082%	0,484	0,0131
3,9167	2,333	5,972	0,1016	100,0%	0,001%	0,503	0,0139	5,936	0,1337	99,97%	0,050%	0,478	0,0138
3,9167	2,667	6,304	0,1038	100,0%	0,000%	0,503	0,0139	6,271	0,1325	99,99%	0,021%	0,476	0,0102
3,9167	3,000	6,638	0,1038	100,0%	0,000%	0,503	0,0139	6,601	0,1244	100,0%	0,000%	0,490	0,0178

A3.9 Kanban Results (2P MC, ST0.5, MTTR1)

Container		WIP		Service Level		Setups	
Amount	Size	Mean	95% CI	Mean	95% CI	Mean	95% CI
4	240	0,436	0,0097	94,45%	0,576%	4,349	0,0457
4	300	0,523	0,0189	96,29%	0,544%	3,565	0,0344
4	360	0,627	0,0345	97,54%	0,583%	3,056	0,0645
4	420	0,736	0,0568	98,39%	0,591%	2,717	0,0431
4	480	0,902	0,0821	99,11%	0,442%	2,425	0,0380
4	540	1,155	0,0905	99,68%	0,296%	2,163	0,0341
4	600	1,384	0,1124	99,86%	0,194%	1,991	0,0384
4	660	1,674	0,0911	99,96%	0,068%	1,777	0,0236
4	720	1,874	0,0837	99,98%	0,034%	1,688	0,0404
4	780	2,076	0,0863	100,0%	0,000%	1,575	0,0346

A3.10 Kanban Results (2P MC, ST1, MTTR1)

Container		WIP		Service Level		Setups	
Amount	Size	Mean	95% CI	Mean	95% CI	Mean	95% CI
4	600	0,660	0,0425	95,32%	0,680%	1,971	0,0524
4	660	0,740	0,0449	96,23%	0,571%	1,808	0,0490
4	780	0,886	0,0759	97,46%	0,651%	1,561	0,0260
4	900	1,065	0,0859	98,49%	0,503%	1,373	0,0231
4	1020	1,324	0,1051	99,28%	0,380%	1,215	0,0291
4	1080	1,720	0,2720	99,61%	0,401%	1,141	0,0275
4	1140	1,988	0,4379	99,81%	0,321%	1,093	0,0224
4	1200	2,243	0,4494	99,91%	0,180%	1,059	0,0249
4	1260	2,669	0,4853	99,92%	0,135%	0,998	0,0250
4	1320	3,226	0,2288	100,0%	0,000%	0,955	0,0246

A3.11 Kanban Results (2P MC, ST2, MTTR1)

Container		WIP		Service Level		Setups	
Amount	Size	Mean	95% CI	Mean	95% CI	Mean	95% CI
4	1440	1,086	0,1280	96,25%	0,724%	0,900	0,0357
4	1620	1,318	0,1483	97,41%	0,726%	0,796	0,0255
4	1860	1,576	0,2293	98,25%	0,684%	0,703	0,0313
4	1980	1,867	0,1695	98,96%	0,634%	0,630	0,0169
4	2160	2,278	0,1601	99,52%	0,288%	0,602	0,0116
4	2280	2,546	0,2911	99,63%	0,277%	0,568	0,0171
4	2400	3,013	0,6026	99,80%	0,243%	0,552	0,0150
4	2460	3,881	0,7353	99,92%	0,131%	0,540	0,0101
4	2520	4,456	0,9542	99,98%	0,055%	0,535	0,0108
4	2580	5,253	1,2243	100,0%	0,000%	0,510	0,0175

A3.12 Small Bucket MRP (2P MC, ST0.5, MTTR1)

Stock		WIP		Service Level		Setups	
Cycle	Safety	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,458	0,000	0,542	0,0064	95,90%	0,329%	1,283	0,0305
0,458	0,167	0,571	0,0054	98,35%	0,205%	1,471	0,0385
0,458	0,333	0,610	0,0149	99,25%	0,225%	1,689	0,0643
0,458	0,667	0,701	0,0492	99,63%	0,210%	1,958	0,1861
0,458	1,000	0,838	0,0645	99,84%	0,103%	1,880	0,1399
0,458	1,333	0,973	0,0786	99,94%	0,051%	1,911	0,1484
0,458	1,667	1,113	0,0910	99,98%	0,028%	1,974	0,1944
0,458	2,000	1,278	0,0917	100,0%	0,006%	1,984	0,1983
0,458	2,333	1,445	0,0918	100,0%	0,000%	1,985	0,1986

A3.13 Small Bucket MRP (2P MC, ST1, MTTR1)

Stock		WIP		Service Level		Setups	
Cycle	Safety	Mean	95% CI	Mean	95% CI	Mean	95% CI
0,667	0,458	0,712	0,0102	96,88%	0,313%	0,890	0,0231
0,667	0,458	0,736	0,0192	98,56%	0,191%	0,975	0,0421
0,667	0,458	0,767	0,0300	98,99%	0,321%	1,064	0,0550
0,667	0,458	0,877	0,0458	99,50%	0,268%	1,068	0,0521
0,667	0,458	1,000	0,0672	99,72%	0,188%	1,059	0,0560
0,667	0,458	1,147	0,0757	99,84%	0,144%	1,050	0,0540
0,667	0,458	1,301	0,0812	99,91%	0,098%	1,045	0,0541
0,667	0,458	1,464	0,0818	99,98%	0,030%	1,046	0,0513
0,667	0,458	1,629	0,0825	100,0%	0,000%	1,054	0,0610

A3.14 Small Bucket MRP (2P MC, ST2, MTTR1)

Stock		WIP		Service Level		Setups	
Cycle	Safety	Mean	95% CI	Mean	95% CI	Mean	95% CI
1,208	0,458	1,222	0,0150	97,16%	0,207%	0,474	0,0084
1,208	0,458	1,248	0,0286	98,59%	0,234%	0,491	0,0149
1,208	0,458	1,302	0,0287	99,20%	0,309%	0,493	0,0083
1,208	0,458	1,423	0,0494	99,63%	0,226%	0,492	0,0130
1,208	0,458	1,562	0,0636	99,79%	0,165%	0,491	0,0098
1,208	0,458	1,703	0,0799	99,89%	0,126%	0,488	0,0106
1,208	0,458	1,860	0,0888	99,93%	0,079%	0,488	0,0111
1,208	0,458	2,020	0,0948	99,99%	0,023%	0,486	0,0118
1,208	0,458	2,185	0,0956	100,0%	0,000%	0,485	0,0123

A3.15 Kanban Results (8P MC, ST0,5, MTTR1)

Container		WIP		Service Level		Setups	
Amount	Size	Mean	95% CI	Mean	95% CI	Mean	95% CI
16	300	1,738	0,0532	94,22%	0,531%	4,503	0,0236
16	360	2,111	0,0604	95,93%	0,410%	3,818	0,0215
16	420	2,530	0,0995	97,15%	0,414%	3,319	0,0167
16	480	2,955	0,1288	98,14%	0,394%	2,933	0,0165
16	540	3,409	0,1379	98,84%	0,309%	2,626	0,0131
16	600	4,060	0,2450	99,47%	0,223%	2,373	0,0151
16	660	5,122	0,5185	99,88%	0,099%	2,172	0,0094
16	720	7,223	0,8391	99,97%	0,059%	1,995	0,0127
16	780	9,298	0,1594	100,0%	0,000%	1,840	0,0122

A3.16 Kanban Results (8P MC, ST1, MTTR1)

Container		WIP		Service Level		Setups	
Amount	Size	Mean	95% CI	Mean	95% CI	Mean	95% CI
16	720	3,280	0,1104	95,89%	0,362%	1,911	0,0119
16	840	3,940	0,1339	97,18%	0,361%	1,659	0,0086
16	900	4,284	0,1798	97,72%	0,416%	1,558	0,0088
16	960	4,629	0,1842	97,99%	0,312%	1,468	0,0074
16	1020	4,941	0,2072	98,50%	0,266%	1,386	0,0084
16	1080	5,514	0,2211	98,89%	0,240%	1,314	0,0069
16	1140	5,941	0,1975	99,09%	0,215%	1,249	0,0053
16	1200	6,455	0,2019	99,36%	0,271%	1,190	0,0083
16	1260	7,224	0,3879	99,67%	0,155%	1,136	0,0069
16	1320	8,858	0,9865	99,92%	0,088%	1,085	0,0061
16	1380	12,253	1,7329	100,0%	0,000%	1,041	0,0071

A3.17 Small Bucket MRP (8P MC, ST0,5, MTTR1)

Stock		WIP		Service Level		Setups	
Cycle	Safety	Mean	95% CI	Mean	95% CI	Mean	95% CI
2,916	0,000	2,970	0,0055	95,87%	0,246%	1,909	0,0638
2,916	0,333	3,190	0,0200	98,72%	0,300%	2,018	0,0921
2,916	0,667	3,481	0,0224	99,43%	0,182%	1,961	0,0565
2,916	1,000	3,780	0,0378	99,57%	0,185%	2,006	0,0633
2,916	1,333	4,080	0,0398	99,70%	0,180%	2,009	0,0748
2,916	1,667	4,384	0,0728	99,77%	0,119%	2,014	0,0864
2,916	2,000	4,686	0,0854	99,86%	0,093%	2,019	0,0918
2,916	2,333	5,010	0,0882	99,96%	0,033%	2,050	0,0900
2,916	2,667	5,356	0,0907	99,98%	0,024%	1,978	0,0928
2,916	3,000	5,687	0,0841	99,99%	0,014%	1,978	0,0963
2,916	3,333	6,015	0,0849	100,0%	0,007%	1,986	0,0978

A3.18 Small Bucket MRP (8P MC, ST1, MTTR1)

Stock		WIP		Service Level		Setups	
Cycle	Safety	Mean	95% CI	Mean	95% CI	Mean	95% CI
4,500	0,000	4,523	0,0094	98,54%	0,128%	1,056	0,0200
4,500	0,333	4,720	0,0327	99,14%	0,151%	1,096	0,0472
4,500	0,667	5,025	0,0388	99,52%	0,153%	1,092	0,0247
4,500	1,000	5,324	0,0563	99,71%	0,105%	1,055	0,0326
4,500	1,333	5,638	0,0503	99,80%	0,087%	1,059	0,0401
4,500	1,667	5,955	0,0573	99,89%	0,089%	1,054	0,0346
4,500	2,000	6,270	0,0657	99,94%	0,050%	1,049	0,0527
4,500	2,333	6,594	0,0754	99,94%	0,061%	1,058	0,0387
4,500	2,667	6,921	0,0816	99,98%	0,018%	1,052	0,0406
4,500	3,000	7,248	0,0874	100,0%	0,006%	1,052	0,0420