Simulation for Digital Manufacturing

A Simulation-based Development Method for Smart Production Concepts of Manufacturing Control Systems in Automotive Industries

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Abstract

Digitalisation has been among the most-often discussed developments of our modern society for decades and it increasingly stretches to manufacturing. Industrial processes merge with information technologies, accelerated by rapidly increasing amount of data and newly developed smart algorithms.

This thesis focuses on demands of digital manufacturing and a neutral evaluation of smart algorithms. Digitalisation is a vast field. Various solutions have been suggested lately and establish further continuously. Companies feel increasingly pressured to amend their structures to smart and agile factories. These wide-spanning refurbishments often lack concrete objectives and clear target figures for successful implementation. This limits the clarity for comparing different solutions. Deriving from a discussion on purposes of digitalisation, simulation and calculation models have been established to evaluate and rate the most valuable approaches.

A test and development system is established, which is suitable to compare different smart production IT solutions. Based on this practical case, a concrete evaluation is described. An exemplary production line is evaluated to find requirements for improved flexibility. After a critical discussion about the suitability of the suggested solution, assistance systems and mathematical models are introduced with which development and optimisation of smart production structures can be implemented in a given manufacturing system.

Zusammenfassung

Digitalisierung gehört seit Jahrzehnten zu den am häufigsten diskutierten Entwicklungen unserer heutigen Gesellschaft und erstreckt sich zunehmend auch auf die Produktion. Industrielle Prozesse verbinden sich mit Informationstechnik, beschleunigt durch rasant steigende Datenmengen und neu entwickelte, smarte Algorithmen.

Diese Arbeit fokussiert sich auf die Anforderungen digitaler Fertigung und eine neutrale Bewertung smarter Algorithmen. Digitalisierung ist ein breites Feld. Verschiedene Lösungen wurden zuletzt vorgeschlagen und entwickeln sich kontinuierlich weiter. Unternehmen stehen zunehmend unter Druck, ihre Strukturen zu smarten und agilen Fabriken zu entwickeln. Diese weitreichenden Erneuerungen lassen oft konkrete Ziele und klare Zielvorgaben für eine erfolgreiche Implementierung vermissen. Dies reduziert die Klarheit im direkten Vergleich verschiedener Lösungen. Ausgehend von einer Diskussion über den Zweck der Digitalisierung, wurden Simulations- und Berechnungsmodelle entwickelt um vielversprechende Anwendungen zu bewerten und zu klassifizieren.

Ein Test- und Entwicklungssystem wurde eingerichtet, um verschiedene smarte IT-Lösungen im Produktionsumfeld vergleichen zu können. Nach einer kritischen Diskussion, in wie fern die vorgeschlagene Lösung geeignet ist, werden Assistenzsysteme und mathematische Modelle vorgestellt, die die Entwicklung und Optimierung smarter Produktionsstrukturen für ein gegebenes Fertigungssystem unterstützt.

Preamble

Numerous publications on digitalisation and Industry 4.0 helped to generate the core topic for this thesis: How can a user find the most valuable strategy, component and solution within a vast choice of proposals that suits best to a particular situation and to a given system.

Producing industries are among the most important sectors in German economy. A major share of the prosperity in developed countries stems from this sector. When the appearance in this field changes, it has to align to successful new strategies. Any risks to this important sector could endanger the economic system. Therefore, it is highly recommended to follow new approaches on smart factories. This thesis is a first starting point for a value discussion on objectives, benefits, but also risks of digitalisation. Targets should be based on concrete figures, ready to use for calculation and simulation. After these objectives of digitalisation were fixed, it took a lot of consideration and development on modelling as well as on digitalisation approaches. An assistance system to support development of smart manufacturing digital production was established.

It is up to production planer, operation staff and manufacturing equipment supplier to decide how much of intelligent automation should be implemented in the factory. This thesis offers a suggestion for target discussion and a suitable model to implement big data analytics or artificial intelligence to keep ahead of a quickly changing, global market that demands new and individual products and quick response on volatile environment.

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First and foremost, I would like to acknowledge and thank Prof. Michael Vielhaber of Saarland University for his continuous support in a vivid project. Critical review on content, format and style brought thoughts in a straight line. Honest words and serious questioning unveiled ambiguous or unclear paths in my argumentation and in project proceeding. Patient aid and solidary encouraged to proceed until a final paper is eventually finished. This let consequently to a thesis, which I could eventually appreciate. For all guidance, help and respect, I am most thankful. I would like to express my gratitude to Prof. Eigner for his support for finalising the thesis and examine the colloquium.

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This work started with a focus on digitalisation and quickly spread to necessarily related areas of research, which forced me to interpret diverse topics, starting with production IT and simulation over to economics, human labour requirements and artificial intelligence. Discussions with friends and colleagues empowered me to progress in various fields of science. I would not want to miss any of these thoughts and words that helped to forge this complete view on an increasingly exciting, but also demanding topic.

Many thanks also to my family and friends for their stabilising support and for thus forcing me to eventually finish my work. Refreshing assistance and strengthening will and abilities on a personal base brought me back on track many times and helped to proceed.

List of Content

List of Abbreviation

AFO – Operation sequence step (German: ArbeitsFOlge)

AML – AutomationML – exchange format

CAD – Computer Aided Design

CIM – Computer Integrated Manufacturing

CNC – Computerized Numerical Control

CPS – Cyber Physical Systems

DKE – German commission for electrical engineering, electronic (Deutsche Kommission für Elektrotechnik Elektronik Informationstechnik)

DMC – Data Matrix Code

ERP – Enterprise Resource Planning

FFS – Flexible Production Systems (German: Flexible FertigungsSysteme)

FMS – Flexible Manufacturing Systems

GDP – Gross domestic product

GVA – Gross value added

HiL – Hardware-in-the-Loop

HMI – Human Machine Interface

I4.0 – Industry 4.0, digitalisation strategy in Germany

IIC – Industrial Internet Consortium

IIoT – Industrial Internet of Thinks

IO – Input- output

IoT – Internet of Things

ISMS – Information Security Management Systems

IT – Information Technology

KPI – Key Performance Indicator

MES – Manufacturing Execution System

MIIT – Ministry of Industry and Information Technology (in China)

MQTT - Message Queuing Telemetry Transport, protocol

NC – Numerical Control

NCK – Numerical Control Kernel

NCU – Numerical Control Unit

NX – Numerical Control Extension

OEE – Overall Equipment Efficiency

OPC – OLE for Process Control, interface

OPC UA – OPC Unified Architecture

PC – Personal Computer

PCU – Programmable Control Unit

PDM – Product Data Management

PFB – File format for Virtual Commissioning visualisation

PG – Programming Device (German: ProgrammierGerät)

PLC – Programmable Logic Control

PSS – Production Control System (German: ProduktionsSteuerungsSystem), MES

QR – Quick Response, identification code

RAMI – Reference Architectural Model Industry 4.0

RFID – Radio-Frequency Identification

SiL – Software-in-the-Loop

SIMULATION Unit – emulation system for Virtual Commissioning by *Siemens*

SGEdit – Component of Virtual Commissioning tool RF::Suite by *EKS InTec*

SGView – Component of Virtual Commissioning tool RF::Suite by *EKS InTec*

SOA – Service-Oriented Architecture

SOP – Start of Production

TA – Technical Availability

TCU – Thin Control Unit

TLX – Task Load Index

VC – Virtual Commission

VDI – Association of German Engineers (German: Verein Deutscher Ingenieure)

VM – Virtual Machine

VR – Virtual Reality

VRML – Virtual Reality Modelling Language

VNCK – Virtual Numerical Control Kernel

WinMOD – Virtual Commissioning tool by *Mewes & Partner*

List of Figures

List of Tables

List of Equations

List of Symbols

B	Benefits
B(fl)	Benefits of Flexibility
fl	Flexibility
C	Costs
C(fl)	Costs of Flexibility
TA	Technical Availability
OEE	Overall Equipment Efficiency
P	Productivity
P_i	Partial Productivity
P_m	Marginal Productivity
P_{mi}	Partial Marginal Productivity
x	Output
y	Input
r_i	Partial Input Factor i
o	Objective

1. Introduction

1.1 Initial Situation

Digitalisation increasingly shapes our world. IT capacity has doubled every 18 month for decades according to Moore's law [Moore 1965]. Exponential growth in data storage capacity continued for decades. The amount of data and the availability of services increase rapidly [Neugebauer 2018]. Ninety percent of all now available data is less than two years old [SINTEF 2016]. With this abundance of available data, plenty of new functions emerge [Miron 2017].

Artificial intelligence, data mining or business intelligence are spreading in various fields of daily life, due to their ability to process big data streams automatically [Raschka and Mirjalili 2017]. Image rendering, automatic customer support services and big data analytics cover a vast variety of smart tasks. Intelligent machines and algorithms adopt human abilities [Russel and Norvig 2016]. Machines can now learn, ponder different opportunities based on learned pattern and they can acquire knowledge and experience, related to previous decisions [Görz et al. 2014]. Thus, computer's and human abilities assimilate. Some computer scientists even see the point of singularity, in which computer have gained equal faculties of cognitive competences as human beings and can optimise themselves independently, commencing soon [Finkenzeller 2015], [Lorenzo 2015]. Machines could combine human abilities in perception, reasoning and learning with calculation abilities of computers and exceed human performance. Nonetheless, human skills are expected to remain necessary for various tasks nonetheless [Horx 2017], [Faltenbacher and Litschel 2016].

Advanced information technologies spread out to manufacturing related IT as well [Mahmoud et al. 2018], [Miron 2017]. Development on intelligent manufacturing IT continues and digitalisation will change industrial structures and processes. Scope and speed of this turnover suggests revolutionary changes of existing IT structures. Earlier Industrial Revolution related to centralised mechanical power, steam power usage and electrifying previously mechanically driven devices. In the now beginning phase, digital content is the key driver. Target is to merge manufacturing experience with IT excellence [acatec 2013].

Examples for upcoming technologies of smart IT can already be found in various fields of manufacturing and is expected to spread further [BMWi 2018a]. Virtual reality entered factory-planning, machine and component vendors develop smart devices and intelligent apps and services for production. Smart production can interconnect departments and plant location virtually. As data acquisition increases, accordingly more information must be exchanged. Data can be stored decentralised in external computer centres, connected databases or cloud via the internet, which requires high-speed internet connections on high volume. Due to transparency on processes, logistics partner can deliver more precisely on demand. Supply difficulties can become obvious earlier and more precisely.

Smart factories connect remote production facilities, plants and locations to a global production network. This includes related departments, like purchase, logistics or external partners. Smart factories are expected to extend flexibility reserves to meet the requirements of changing markets [BMBF 2017], [bitkom 2017], [Pawellek 2014]. The needs for changes are manifold: costs, availability of resources and qualified personal, infrastructure and adjustment to economic, social or political conditions [Cummins 2017].

Different from previous phases of Industrial Revolution, digitalisation is not only driven and scheduled by technological improvement in computer science itself, but the development is further accelerated by strategies and political projects [Banholzer 2018]. Guidelines from economy and science support digitalisation. In Germany for example, politics, economy and science collaborate under the headword Fourth Industrial Revolution, Industry 4.0 or short I4.0 [Hannover Fair 2011]. Other countries have similar strategies on Smart Factory, and Internet of Things.

1.2 Motivation

Intelligent algorithms have already become widely common in daily life [Sendler 2018]. Many companies focus on strategic schemes to alter production structures quickly. It can be expected that exceedingly volatile markets and mass customisation might sanction companies, which stick too long to old business models [Bauernhansl 2016]. New products must enter the market faster and more frequently [Müller et al. 2013a]. IT business cannot refer to a long history of experience, but has emerged only some decades ago. However, information technology facilitates the success of other technological domains [Spiekermann 2016].

Although many relevant algorithms and methods would be ready to use on the shopfloor and the necessity of digital transformation is widely discussed, Smart Factory is still not common use in manufacturing [Bauernhansl 2016], [Sendler 2018]. One quarter of the surveyed companies struggle with digitalisation, especially in the industrial sector [BMWi 2018]. Introduction of artificial intelligence is still limited due to various implementation issues [Schaubenberger 2018] and operation staff often implements new structures only carefully to avoid risks. Experience shows that if technical availability of the machines, stable production and output cannot be guaranteed, responsible production manager resign from new systems rather than to venture stoppages which makes them unable to deliver confidently and right on schedule.

Concepts on flexible production lines have already been a popular research topic in machining development in previous decades [Maleki 1991], [Ranky 1990], [Tempelmeier and Kuhn 1993]. The purpose of flexible automation in manufacturing is to produce economically different parts in random sequence and changing batch size [Kief 1998].Targets for flexible machining are especially reduction of time, costs and staff. Fully automated lines should dispense operation staff completely in the end [Dostal et al. 1982].

Since the 1970s, flexible production systems have been in development in machining. Target is to increase productivity to get close to its theoretical maximum, because machine, staff and production hours in general are expensive in machining. Technical availability of the machines of more than 90% was addressed. Costs for tooling should be minimised by extending the usage of tools until close to the end of its tool life. In the established system, 30 machines should be able to produce 100 different part types. In addition, the workforce should have been reduced to save labour costs and efforts. Planning staff and maintenance took advantage from computer aid (CAD, CIM etc.) for transparent machining processes with enhanced product design and production planning [Posse-Dölken 2006].

However, introduction of these concepts was accompanied by various obstacles. Operation staff was exceedingly demanded in flexible machining lines. The targets on availability and stability could not be met. Therefore, productivity, quality and operating grade could not outweigh higher cost for extended automation. Instead, flexibly designed transfer lines prevailed due to better performance [Posse-Dölken 2006]. The results have not been realised to the expected extend. Work preparation indeed got more effective as information of construction is made better available for production program scheduling. More information is used for multiple purposes. Engineering tools have improve a lot nonetheless, high invest and planning costs due to complexity made the system expensive and inefficient [ElMaraghy 2009]. Larger systems became complex, fault-prone and lack overview [Kief 1998]. Small units are less failure effected.

Nowadays expectations are high on digitalisation [Reinnarth et al. 2018]. It especially deals with flexible production lines to prepare changeable manufacturing [Müller et al. 2013], [Schenk et al. 2014]. Smart production is said to increase flexibility and transparency of production. Processes are getting decoupled and independent [Bauernhansl 2016]. Conventional concepts of assembly lines have a strict sequence of stations due to the assembly routines [Konold and Reger 2009]. Each station hosts one or a few mounting operations. In general, the products must be passed through the line station by station, because the assembly workflow is often depending on previous processes. For example, a fuel tank must be mounted first before it can be filled. The cycle time is nearly the same for each station. If one station stops, the whole line would need to wait for this one to be repaired, unless redundancy or bypassing is prepared. For stations with higher risk of breakdowns, bypass stations at least with manual processes must be installed as an emergency strategy. This concept of sequentially lined up cells is also similar for other faculties such as body in white, paint shop or car assembly.

In contrast to these conventional structures, intelligent systems allow adjusting the process sequence of the parts [acatec 2013]. It is an alignment for flexibility and individualised production. Self-controlling work pieces have access to necessary information on the production process. They get aware about their recent and targeted state and can control their path through the operation and therefore become active participant [VDI 2011]. Thus, products and production resources negotiate the path through the line. The workflow is depending on the availability of manufacturing capacities.

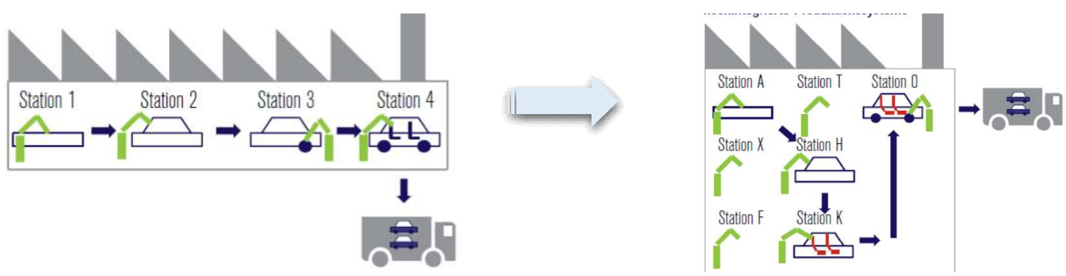


Figure 1: A Vision on Future Production Systems, Source: [acatec 2013]

The workpiece may skip operations if the next machine is still engaged or blocked for the moment. Another process can be done first and the skipped station will be visited later. The product finds its way through different manufacturing resources. The part receives awareness about recent state and demanded further operation. It uses and consecutively adds information to the product's data sets. Data storage and quick data transfer will become more important with increasing amount of information. Production will be self-controlled. This enables the products to run through different processes in an individual sequence, which comes close to batch size 1 production or marginal cost 0 [acatec 2013].

Decoupled and flexibly integrated machines increase adjustability to changing environment [acatec 2013], [Zäh et al. 2009]. The machinery can be adjusted quicker, new machines can be added or the sequence can be changed with limited influence on the previous setting. Independent processes would enable to arrange stations more adjustable, allow different cycle times, and skip a station or change sequence. Cells can be positioned flexibly and further machines can be added easily. This improves re-use and expanding machine pools. Currently surplus facilities can be switched off or to energy save mode. Resource sharing could open up opportunities for efficiency raise like shared resources. Agile order management and coordination of manufacturing processes allow production of various goods at the same time [BMBF 2013].

Smart automation doubtlessly is an attractive topic and numerous companies welcome this development. In the upcoming years and decades, companies will expectedly increase their efforts to integrate IT solutions effectively, fast and noiselessly. Implementation of smart production structures might become risky when the development time is too short. Large production facilities, production lines or plants enclose massive amounts of investment, which will expectedly increase with digital refurbishment [Miron 2017]. When this financial stress is involved, manufacturing facilities must continuously run to pay off their investment. Any breakdown would cause tremendous losses. When system complexity increases, companies regularly back out of high-tech solutions and turn back to less sophisticated technologies that are easier to operate. A study published by the Fraunhofer Institute for System and Innovation Research (ISI) unveiled that for nearly a third of the examined companies highly automated solutions do not meet their expectations appropriately [Lay and Schirmeister 2001].

Lay and Schirrmeister found that in up to 24% of the plants, the level of automation is reduced again. Complex structures are hard to control and tend to reduce intuitive operability. At a certain point of complexity, the operator has too many influences to observe so that he is simply not able to find the right parameter on time. Faults and malfunctions stay hidden and are hard to detect. Maintenance is getting more demanding. Companies, which have lowered their automation level, regularly do not return to high-tech strategies; they have painfully learned that their targets for quality and delivery date adherence are fulfilled better with easier systems.

Even more astonishingly, the reasons to reduce the complexity of over-engineered production lines match with the most important objectives of digitalisation strategy: over-engineered systems lack flexibility in production volume and derivatives, individually customised products or production in smaller batches is uneconomical with over-engineered machines and quality targets and observance of delivery due dates are not met satisfactorily. High investment and maintenance costs reduce the overall efficiency of smart solutions. 23% to 38% of the questioned companies with high growth have already or plan to reduce their automation level [Lay and Schirmeister 2001].

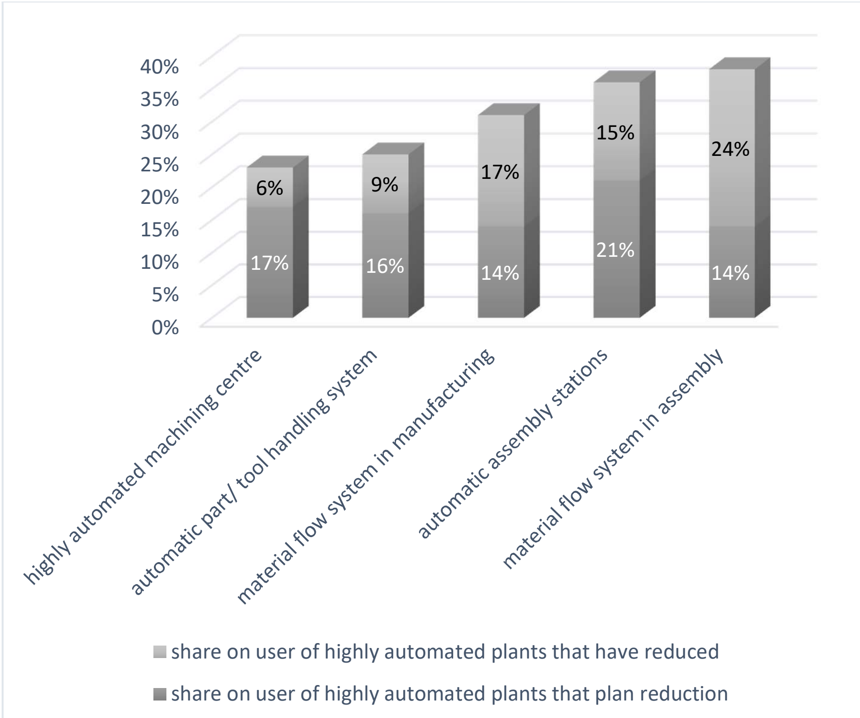


Figure 2: Share of Companies that Reduce or Plan to Reduce Automation Level due to Over-Engineering, Source: [Lay and Schirmeister 2001]

Too complex automation rather reduces production yields, as even Tesla had to realise [Grundhoff 2018]. Rapid transformation bares severe risks on stability of productive systems. Therefore, implementing smart solutions must be prepared carefully in order to avoid inappropriately working systems or production losses due to breakdowns. For highly sophisticated systems, complexity increases. Systems might become too complex to be managed effectively by human operators, as too much information must be handled. Planning reliability decreases [Kofler 2018].

Producing industries is one of the most important sectors in German economy. Labour is centralised in factories, a major share of the spendable income of industrial nation’s stems from industrial production payments and loans, as the figures for German gross value added below show [DESTATIS 2017].

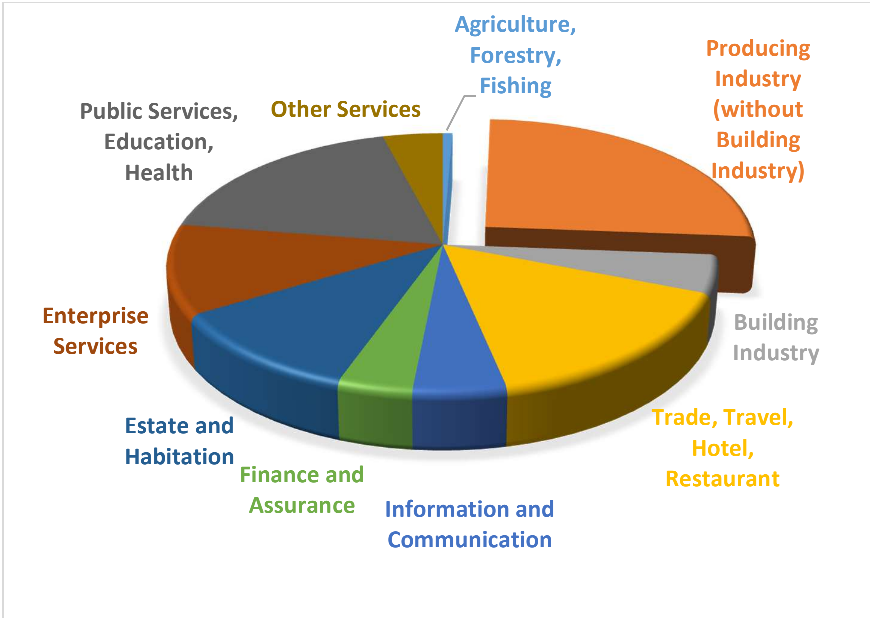


Figure 3: Share of Gross Value Added GVA in Germany, Source [DESTATIS 2017]

In Germany, producing industries hold the major share of the total revenue, far more compared to information and communication industry. With 772.3 billion €, it has the biggest share of German gross value added of in total 3 134.1 billion €. Information and communication sector still keeps a minor influence with 136.9 billion €. Information technology is on the rise, but income figures show that the influence of production is still far more important. However, IT is expected to take major influence on industry [DESTATIS 2017].

Table 1: Gross Value added GVA in Billion € per Year in Germany, Source [DESTATIS 2017]

Agriculture, Forestry, Fishing	18,0
Producing Industry (without Building Industry)	722,3
Building Industry	134,6
Trade, Travel, Hotel, Restaurant	443,1
Information and Communication	136,9
Finance and Assurance	110,8
Estate and Habitation	307,0
Enterprise Services	316,4
Public Services, Education, Health	519,0
Other Services	114,1
Total	**2.822,2**

Innovative Start-Ups launch businesses for smart inventions in centres such as Silicon Valley, California, Los Angeles, London, Singapore or Tel Aviv. However, information technology facilitates the success of other technological domains [Spiekermann 2016]. For Germany, production sector has to be kept vivid to remain among the leading industrial nations. Tendency to adjust this sector dramatically must be adopted appropriately to catch up with beneficial changes when new structures become competitive. Otherwise, the most important industrial sector in Germany could lose competitiveness. The possibility to lose track with market and customers is too risky to refuse preparation future development. History showed, how long misled structural changes can demand recovering: The effects on the missed changes are long lasting as it can be seen in various examples of only partly transformed heavy industry areas. Some areas could not follow the changes from heavy industry (coal and steel) to modern manufacturing: West Midlands in England, the Ruhr Area in Germany or parts of China. “Digitization is increasingly casting doubt on the sustainability of traditional business models” [McKinsey 2016]. Therefore, developments on digitalisation must be observed carefully and beneficial solutions must be implemented to avoid losing the influence of the industrial sector [Bauernhansl 2016].

Assets are centralised in factories. Industry drives technological research and development. Industry is a key element of modern society as it concentrates a lot of facilities, labour and prosperity of developed countries. Since industrialisation and the rise of capitalism, production strives for perfect processes and highest possible efficiency and productivity. Process innovation improved efficiency and rationalisation went on during the last centuries [Brynjolfsson 2016]. Regarding the described visions, digital transformation as discussed recently could change the structure of manufacturing completely from data acquisition, transfer, storage and processing. Smart production methods are highly welcome and lots of research and development is ongoing. The appearance of modern factories is likely to change continuously and rapidly in the upcoming decades. It can be expected that this transformation must be prepared carefully, as stability of production will rely especially on manufacturing IT. Due to digitalisation tendencies, efforts for production planning projects accumulate rather in IT issues. A range of new technologies emerges on the machinery market.

Automotive industry regularly leads innovation and development of new systems and concepts [Kropik 2009]. Car production is a serial process of complex products in a large variety. Efficiency measures have a big impact on the system. Therefore, car industry is a major driver for innovation. However, IT and organisation still cover nearly 50% of the whole production costs although massive innovations in these fields have been introduced successfully [Kropik 2009]. Though the need for improvement is commonly agreed, the sheer amount of approaches leaves many decision taker in industry puzzled about which solution is suitable. The selection of smart devices and services for improved manufacturing increased tremendously recently and will further amend production technology. Companies are irritated by the choice of possible solutions [Kleemann and Becker 2018]. Benefits and costs are hard to estimate in advance for new applications. The question remains unanswered, how smart systems can efficiently be implemented in manufacturing without corrupting running processes. The limits of complexity are often under-estimated in early project phases and system reductions afterwards are hardly ever satisfactory [Lay and Schirmeister 2001].

Various solutions and approaches for smart production emerge on the market that might fit differently well for a given production system. However, clear calculation of costs and benefits remain unclear. This huge choice makes it difficult to find a suitable solution that fits best to a particular situation and production environment. Main task for this thesis is to enable to design Smart Factory best suitable for a certain situation or enterprise appropriately. Support for software implementation with early evaluation and transparency about risks and benefits of smart production solutions is needed. A clear calculation strategy must enable planning personal and decision-maker to detect the most beneficial solution out of many opportunities.

1.3 Objectives

Change intensive digitalisation strategies bare unforeseeable risks for project success, agreed project targets, costs and timeline adherence. As IT competences improve rapidly, upgrades must be implemented more regularly to keep up to date. The mechanical construction of a production plant is often kept for 15 or 20 years, whereas the IT infrastructure can amend in the meantime several times. Production is in continuous change and therefore, the structure must be adjusted during the lifetime of the plant. Requirements on flexibility and changeability increases due to customer demand, markets and environment [Schenk et al. 2014].

Strategic amendments demand a range of IT system innovations for manufacturing, logistics, sales and services. To launch smart factories successfully, IT landscape must be established very carefully to avoid wrong investments, machine malfunction, over-complex lines and breakdown. Digitalisation in producing industries will require various example projects to set up recently developing smart factories. Scale and range of the digital turnover suggests sufficient testing.

Preparation of smart production IT must include early testing of systems that are in development to be used in production network. Without early examination and approval, many problems occur not before the production volume increases. Lately detected malfunctions are extremely expensive [Sauer et al. 2010]. Simulation helps to reduce risks to an acceptable and predictable limit. A test method is needed to compare and rate smart production approaches. Calculation and simulation for planning and purchase decisions are essential. Production, planning and related departments need to understand the planned control system early in the project in order to steer the needed developments appropriately. To improve a complex production structure, possibly globally spread over different factories and locations, a production-parallel model is necessary to provide an exact and concrete overview on the system.

Suitable to the simulation environment, an evaluation method must enable planning teams to compare and rate effects of new structures. Smart production must meet the challenges of industry that may vary as well in time and space as in the particular, concrete situation in the factory environment of the company. A qualified evaluation method for Smart Factory approaches should enable the user to understand new structures early before implementation. Changes can be considered early enough to avoid inappropriately working machines or costly amendments late in the project. Benefits of innovation and strategic targets are not easy to predict or calculate. Smart Factory approaches are hard to rate. This requires an open and critical discussion about purposes, benefits and risks of digitalisation strategies. A performance indication system must enable planning departments to check the quality of IT solutions and keep the project on a successful track.

This thesis will suggest both a simulation environment and an evaluation method to test digitalisation scenarios and enhance the liability of new IT systems. Main research questions for this thesis therefore are how a suitable simulation model must be set up, how the testing can be evaluated and which results are expectable. A method must rate digitalisation approaches and calculate the benefits to compare them with the costs of integration.

Initial research questions are:

1. Does a simulation model allow sufficient testing on smart production IT approaches and how can the model be set up?
2. How can smart production systems be evaluated and compared?
3. Which results can be derived from a simulation and evaluation method for Smart Factory approaches?

1.4 Research Method and Structure of Work

The structure for this study follows the research design study as described by Blessing and Chakrabati [Blessing and Chakrabati 2009].

First step of the thesis is the *research clarification*. Its main purpose is to clarify the recent state of technology and research as well as the circumstances that require further development. The background of the thesis must be described precisely. This includes the environment in which research is started and the targeted situation, the thesis should lead to. For this thesis, the initial idea for research is to test and evaluate smart production systems. The initial situation, motivation and objectives must be declared. Deriving from this fundament, the structure of this work must be established. The necessity for further research should become obvious and initial research questions must be defined.

After hints to initiate a study have become concrete, the next step, *descriptive study I*, is to describe the task as detailed as possible. Crucial influences for the research task must be unveiled with a literature and market study. For this thesis, the objectives are firstly to find a useful simulation environment and secondly to define concrete performance indicators for digitalisation that can be compared and optimised. This demands an overview on production IT, simulation methods, manufacturing planning processes and digitalisation approaches.

An initial analysis of literature and state of the art solutions establishes which methods are commonly in place for simulation of production automation. Tools and methods for testing and simulation of production systems must be specified to find suitable solutions. Proposals on current state of the art production simulation that are available on the market are compared, but also relevant research and development approaches are included. From this recent state of technology and science, deficits of already existing methods for testing of smart production systems are deduced. A possible setting is chosen to start with.

After the introduction on state-of-the-art manufacturing IT, simulation methods and tools and production planning processes, a sketch of future production solutions is drawn. This includes especially the latest development of technology and industry until the recent phase of increasing digitalisation and suggestions for smart production. Digitalisation of manufacturing processes is widely discussed, but visions lead to various, diverse directions. The picture on what digitalisation means or what Industry 4.0 includes is blurred. A clear and agreed definition of the demand and requirements of Industry 4.0 or Internet of Things is still not released. For this thesis, different approaches for Internet of Things, cyber physical systems or decentralised control systems are discussed in order to derive concrete figures of the needs and opportunities for producing industries. Demands of production planning and manufacturers must be understood.

An initial analysis of literature and state-of-the-arts solutions examines what smart production can look like. This picture describes demands and requirements of common visions of Smart Factory. Based on the opportunities and risks for producing industries, a discussion on future production technology and Smart Factory approaches examines possibilities to compare and rate IT structures.

In the following *prescriptive study*, both the simulation environment and a systematic structure of relevant performance figures must be established and build up. Starting with already existing tools and methods, a first example test system is set up. A test evaluation for concrete production lines must allow comparing and rating of newly established IT solutions for smart manufacturing approaches.

First task is to define target production figures that are capable to describe a well-established digital manufacturing system. Performance indicators are regularly agreed to follow up the progress of a planning, of an improvement project or of daily production. However, digitalisation demands other targets, but they are not commonly agreed. The field of digitalisation is wide and different companies or even parts of the same company and different departments might define different targets. A close look at achievements and benefits is valuable to concentrate on the most advantageous approaches of digitalisation. A selection of values for digitalisation is chosen and possibilities to establish key performance figures to compare and rate different solutions based on these objectives is examined. A discussion about the targets for smart production approaches highlights the main criteria to be tested with the established evaluation method. Result of this discussion should be practical constrains to simulate and calculate benefits and costs for digitalisation approaches. Comparison measures for production IT systems must be prepared. With extracting figures and performance indicator from machines, it should be possible to analyse different concepts reasonably.

A simulation model that fits to the requirements of the considered manufacturing IT must be established. Simulation can provide a detailed, but abstracted view on the system, which is to be examined. Suitable simulation programs and approaches are compared and evaluated. If available, a commercial tool should be chosen as starting point for the test environment. After the study on state-of-the-art systems and analysis on available methods and recent developments for simulation of production systems in descriptive study I, the best starting point for this work can be chosen. The model must be able to cover large manufacturing structures. At the same time, the program code of the production software must be described in detail. This is especially for algorithms that optimise autonomously like big data analytics, pattern recognition, machine learning and artificial intelligence, because they can hardly be abstracted appropriately. A simulation model to extract a setting of empirical data is established in order to extract numbers and figures from the system. Possibly necessary adjustments are established.

The usability of the found solution is discussed in *descriptive study II*. It describes to what extend the developed method would fit to the task of testing, evaluation and rating of smart production systems. The described simulation model is verified on usability for modelling digital manufacturing systems and necessary adjustments are summed up. The suitability for the given purpose is described and deficits are summed up. Efficiency and effectiveness of the test system are discussed and suggestions for improvement are given.

Together with this simulation setting, a method must be developed to evaluate and rate smart production. In order to distinguish effectiveness and efficiency of different IT approaches, objectives for future production must be defined. An evaluation method must enable the planning team to analyse different production strategies. Therefore, a sufficient method on how manufacturing can be compared and rated and how influential figures can be extracted from a production system must be provided. This method must be tested and proved with the previously defined comparison data. The suggested calculation method is validated. One concrete example for a suitable evaluation environment is established and put into relation with other relevant systems. A data set from a real, productive manufacturing system is evaluated to find patterns that show the systems' performance. A suitable method must allow extracting information about a system that display relevant parameters related to the objectives of digitalisation.

The conclusion sums up the work. An outlook suggests future development for the established system.

This thesis describes methods to simulate and evaluate Smart Factory approaches. It examines smart production with the focus on necessary performance figures for rating and comparison. IT for different industrial branches vary from manufacturing like machining and assembly process technology like chemistry, pharmacy, oil and gas exploration, or systems for energy sector. Smart Factory approaches are widely discussed in event discrete manufacturing processes, but also for continuous processes. Process automation for automotive industry is often continuous control. Energy supply and distribution, chemical industry, steal and other fields show varying figures, but the basic ideas and rules are similar. Certain similarities to other branches are obvious, but won' be explained in detail here. This work will concentrate on automotive industry. Therefore, manufacturing related approaches are preferred, especially related to machining. Furthermore, the work originates in Germany. Strategies in other countries will be depict briefly. However, the focus of the work is on German industrial structures.

Table 2: Research Structure

Research clarification	Introduction	Initial Situation
		Motivation
		Objectives
		Research Method
Descriptive study I	Fundamentals	Production IT
		Simulation for Production Software
		Factory Planning
		Product and Production Planning
		Evaluation of Production Systems
	State of the Art	Historical Background
		Demands and Requirements
		Digitalisation in Industry
		Smart Systems
		Targets for Digitalisation
		Digitalisation Strategies
	Deficit of Existing Solutions	
	Elaboration of the Task	
Prescriptive study	Performance Indicators for Digitalisation	Adjust to Changing Environment
		Economic Contribution
		Transparency
	Simulation Model Setup	Requirements
		Exemplary Production System
		Simulation Software
Descriptive study II	Verification	Extend Usage
		Reduce System Complexity
		Standardisation
		Automatic Model Generation
		Software-in-the-Loop
		Continuous Improvement
	Validation	
	Concept	Assistance Systems
		Mathematic Model
		Flexible System Architecture
Conclusion		
Outlook		

2. Fundamentals

2.1 Production IT

Depending on the industrial sector, automation is optimised to its main purposes in process technology [Früh et al. 2018], manufacturing [Weber 2017], [Weck and Brecher 2006] or material logistic control [Günthner et al. 2012], [ten Hompel et al. 2007]. Even within one company, control systems vary for different divisions and departments [Kropik 2009], such as body-in-white, paint shop, machining or carbon fibre production in automotive industries. The control system landscape in producing industry depends on its purposes, structure, and complexity. High-level enterprise control and data acquisition is often PC-based and connected to operative PLC level [Vogel-Heuser and Wannagat 2009]. On the shop floor, PLC, robots and NC machining centres are common. Body-in-white and paint-shop need robots for movement of welding or painting tools. IT systems in car manufacturing focus on different technologies: Machining processes concentrate on numerical control units CNC, optimised for cutting and drilling operations. Lead PLC or PC-based MES system connect office and shopfloor environment [Wellenreuther and Zastrow 2015].

IT systems in production environment cover functions from order assignment to delivery and from the enterprise execution level to the field level. ISA-95 defines five IT levels [Früh et al. 2018]:

- Business (ERP)
- Execution (MES)
- Process
- Control
- Field bus

ERP – Enterprise Resource Planning is an information system for business relations [Kurbel 2016] including customers' orders, supplier requests and logistics, in-house production orders, external purchase and customer delivery. Manufacturer use ERP systems to share and operate relevant information about order, production and offer that are relevant for different departments and locations of the company [Kropik 2009]. Numerous functions, which have been separated previously, have been integrated to one comprehensive ERP system with a shared data backbone. A platform provides a range of functions for purchase, order release, manufacturing and delivery for several related entities in the company and related partners.

The MES – Manufacturing Execution System distributes control demands from superior ERP to the production and automation level of PLC, NC and robot control [Kropik 2009]. It schedules production, provides plans for daily tasks, like gauge plans and tool data information and are used for documentation [Früh et al. 2018]. Order information can be extracted from the ERP system. Data from the shopfloor, process data and product information is sent to the MES system and vice versa [Antonio et al. 2017], [Mahmoud et al. 2018].

Control systems spread through different levels of the company depending on the purpose [Lunze 2016]:

- Enterprise Control Level:
  Enterprise strategy, sales, human resource, financial planning
- Production Control Level:
  Business and technical functions, logistics, quality control
- Factory Control Level:
  Material and staff planning
- Process Control Level:
  Observe and optimise processes
- Fieldbus Level:
  Measure and control sensors and actors

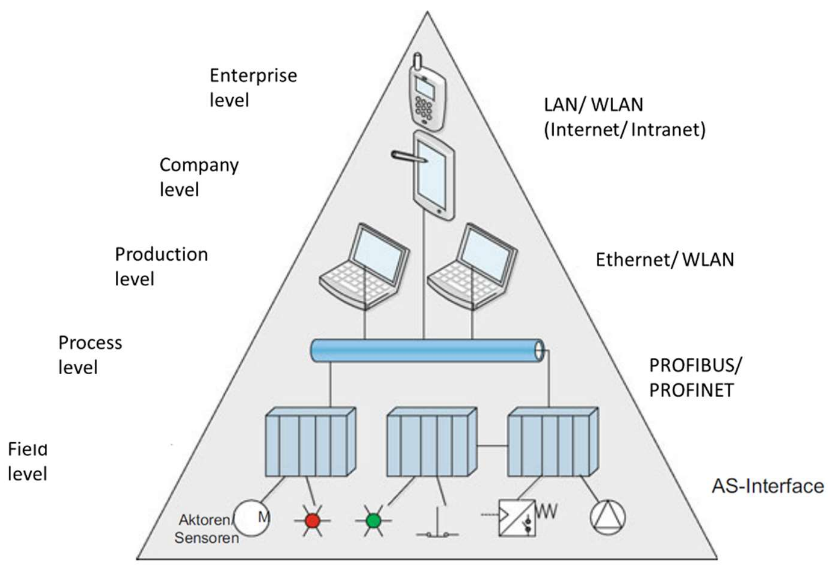


Figure 4: Automation Levels, Source [Heinrich et al. 2017]

On the shop floor, automation connects sensors and actors in the field level with PLC, NC or robot programs. The operation software must be linked to office and server levels. The execution system interconnects fieldbus instruments [Kropik 2009]. It enables observation and evaluation and builds a user-friendly operation system for the manufacturing processes.

On ERP level, the overall company's interests are managed. PCs are common in office environment, whereas SPS or robots are well established for harsh industrial environment. They are designed to run without interruption for months and years. Data exchange format allows connecting different levels: field bus, Ethernet-TCP/IP or ProFiNet IO [Wellenreuther and Zastrow 2015]. Internet of Things communication is often based on common protocols like OPC UA [Rinaldi 2016], [Vasters 2017] or MQTT [Obermaier 2017].

For Industry 4.0, reference architectures are in discussion. The Reference Architectural Model Industry 4.0 RAMI 4.0 distinguishes seven categories of system size [ZVEI 2015b]:

- Product
- Field Device
- Control Device
- Station
- Work Centre
- Enterprise
- Connected World

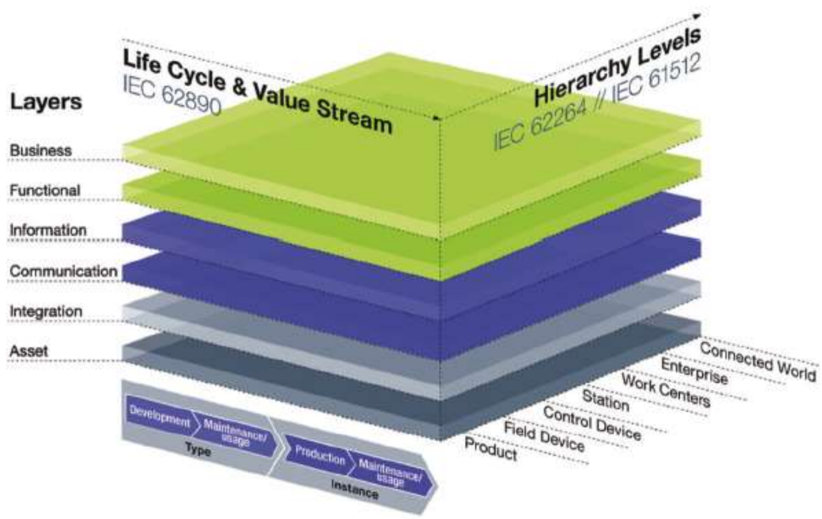


Figure 5: Reference Architecture Model Industry 4.0, Source: [ZVEI 2015b]

2.2 Simulation for Production Software

Simulation is a method to examine a system by abstracting relevant components of this system in order to extract additional knowledge about this system [Hedtstück 2013], [Kühn 2006]. Models often retain only to the relevant characteristics of the object to be observed [Williams 2013]. Scenarios can be compared by changing input parameters and observing, how the output variables react to these changes. A model simplifies a sophisticated system and therefore enables evaluation and decision making on complex structures [Acker 2011]. It is independent from the real machine and can be used before the actual machine is finished and when the real machine is in production and cannot be used for tests. Basic information is described in VDI norm 3633 [VDI 3633].

Main aspects of a real system are abstracted for simulation. With this model, experiments can be conducted and transferred to the real system. Parameter adjustments can be done to vary and improve the concept. A simulation model is independent from the original system [Borshchev 2013]. Therefore, the model of a production facility can be tested before the real production line is completely build up. It can be abstracted and therefore does not need the whole content. However, all details that are spared might corrupt the results of the evaluation and therefore bare the risk of incorrect conclusions. Therefore, verification and validation is needed to secure appropriate simulation [Wenzel et al. 2008]. Production simulation enables planners to evaluate systems independently from the real machine. Thus, concepts can be established before installing the machines. During operation, the model can replace tests with the production line, which reduces downtimes, and risks of breakages can be avoided. A running machine can be optimised independent from production schedule and without any effect on output and critical facilities.

A simulation task can be divided into phases [VDI 3633]:

- Task definition
- System analysis
- Model forming
- Implementing
- Experiment
- Analysis

Manufacturing facilities are event-discrete systems [Lunze 2006]. Most of the controls logic is non-continuous. Event-discrete systems can be modelled with state machines, petri nets or Markov chains. Logic models describe which states can be adopted by this system. Stochastic models include how likely different states are. Time-based models integrate the duration of transitions or waiting times. Time and stochastic constrains can be combined in one model.

Planning uses simulation on different automation levels of the automation pyramid: signal level (input/ output), field level, PLC, MES and ERP. Dohr proposed a comprehensive simulation method for product development [Dohr 2014]. The European project pathfinder examines simulation and analysis methods to inform factories of the future (FoF) about simulation approaches [pathfinder 2014].

2.2.1 PLC and Robot Simulation Tools

A Range of different PLC simulation programs is available to test the PLC's logic reaction under the influence of parameter settings and changes, for example PLCsim [Siemens 2018a] and PLCSIM Advanced [Siemens 2018b] provided by *Siemens* or Trysim by *Cephalos GmbH* [Cephalos 2018]. Especially software developers or maintenance with experience in the software code use PLC simulation tools to check signal changes. These programs offer a detailed simulation of the PLC. Larger structures lack the overview over the whole system and are therefore less intuitive with PLC simulation.

For robot cells, different suppliers offer offline software to test the robot program. Programs like RobCAD [Siemens 2018c], ROBOGUIDE [Fanuc 2018], RF::RobSim [EKS InTec 2018] or RobotStudio [ABB 2018] test program, robot paths and collision. Robot simulation tools are used for Virtual Commissioning (chapter 2.2.2 *Virtual Commissioning*). Machine vendors support test equipment to check software and parametrisation of their components.

Production processes themselves, such as cutting process for machining centre can be simulated with kinematic calculation or multi-body simulation. Approaches for machining centres address the cutting processes themselves.

Other simulation methods originate not only in manufacturing environment, but they can be used for production simulation as well. Simulation and calculation routines can be evaluated with standard software development toolkits in C, C++, python or Visual Basics. MATLAB/ SIMULINK is a standard simulation system for advanced product development. It also includes toolboxes for control systems, mathematics or optimisation [MathWorks 2018]. Machine simulation on a sophisticated, e.g. dynamical level is possible [Zirn and Weikert 2006].

2.2.2 Virtual Commissioning

On station and work centre level, Virtual Commissioning is used during planning projects for quality check and pre-acceptance of software on an emulated or physically existing control system [Mewes and Wegener 2009], [Reinhart and Wünsch 2007], [Zäh and Wünsch 2005]. It is described in VDI norm 3693 [VDI 3693]. Production facilities can be tested in early construction phases before the machines are erected on the shopfloor. The control system (PLC, NC, robot control) is connected to a virtualised plant model that simulates the behaviour of the manufacturing system. Thus, software quality can be checked at the vendor's and pre-acceptance is possible in earlier project phases. With early software testing, the remaining commissioning time on the shopfloor reduces. Faults that are found in earlier project phases can be fixed cheaper at the vendor's than at the building site. Earlier start of production safes costs remarkably. However, the effort to build the model must be added to the project costs.

Virtual Commissioning includes a visualisation to improve the understanding for a human observer. 3D visualisation undoubtedly improves the intuitive comprehension for programmers and commissioning and operation staff. For visualisation setup, two methods are common. CAD construction data can be loaded and the kinematics is adjusted or library elements of the components are loaded. If CAD data are available, the 3D geometric information can be imported, which provides an exact view on the mechanics. With a continuous engineering platform and database, CAD data should be available. However, Mewes & Partner describe the problem to receive the necessary construction data on time, proper description of the process, and consistency and transparency of the delivered data. Requested data will be updated or adjusted during commissioning. However, preparing these data early before the real commissioning will improve the process [Mewes 2007].

There is a variety of software tools available for Virtual Commissioning. Two categories can be distinguished, depending on the main purpose [Bergert et al. 2009]: The first one is rather related to the control systems, the other one stems from Digital Factory. Automation related tools focus on the system's behaviour. Tools for the Digital Factory use 3D data derived from mechanical construction and add the behaviour model afterwards.

Standard programs for Digital Factory are for example RF::Suite (*EKS Intec*) or Process Simulate Commissioning (*Siemens*). Examples for automation focused software solution are WinMOD (*Mewes & Partner*), Simit (*Siemens*) or Virtuos (*ISG*)

RF::Suite by EKS InTec is a toolbox for various tasks in production simulation. Data preparation tools for virtualisation of production facilities supports construction data exchange and adjustment. Visualisation, virtual robot controls and behaviour modelling enable pre-acceptance tests for production automation. Robot connection and emulation tools and analysis programs enhance the simulation [EKS 2018].

Mewes & Partner offer with WinMOD a software to emulate PLCs and test program behaviour [Mewes 2018]. Different drivers are available to connect to a number of protocols. Two visualisation systems are provided. WinMOD 3DView allows a behaviour model to communicate with a 3D VRML model. This solution is suitable if CAD construction data are read in. Simline is a library-based system for standard elements. Symbols and active elements change colour and layout depending on the PLC signal status indicate system states.

Signals can be read from and written into the control system. The behaviour model is set up graphically and imitates the behaviour corresponding to the input and output signal exchange. The output signals of the test PLC are read into the WinMOD model and related to the behaviour models, the PLC receives corresponding input signals.

Simit works similar to WinMOD. It is provided by *Siemens* and it contains a library that can be extended with self-designed elements. A 3D visualisation tool allows importing VRML data. It can be coupled with OPC or shared memory interface. 2D animation is also available.

Both WinMOD and Simit need an emulation system to connect to the control system. SIMULATIONUnit by *Siemens* (previously called Simba) emulates not existing bus participants and enables to connect simulation software with the control system. The real-time simulation system SIMULATIONUnit offers twofold function: it emulate not actually connected field bus devices and connect the behaviour model with the control system.

F.EE provides with FE.Screen a simulation system for simulation and Virtual Commissioning [F.EE 2018].

ISG Virtuos uses a PCI Profibus card that is integrated in the simulation PC and TwinCAT software to connect to the control unit. Simulation boxes are not needed to connect the control unit. Library elements are available to link data exchange easily to Sinumerik and Simotion components.

For tooling machines, *Siemens* developed a virtual NC kernel. The project VNCK Ramp up / 2 intends to develop a virtual NC for exceeded virtual machining centre with logics content [Denkena et al. 2008]. It enables Virtual Commissioning of NC machines without Sinumerik Hardware. Baudisch developed a detailed machining centre simulation based on virtual machine control system [Baudisch 2002]. VNCK emulates Sinumerik NC system. The calculation of the NC for cutting processes is extended to longer cycle time, which supports calculation and simulation during this process. For a sequence simulation, real-time simulation is needed. DMG Virtual Machine is a tool to run a cutting or drilling process on a virtual machine [DMG Mori]. Hefts describes the problem about simulation PLC part of a NC machine [Herfts 2014].

Schneider et al. describe test scenarios for Virtual Commissioning firstly for program performance test and secondly for failure simulation [Schneider et al. 2014]. According to Strigl, test settings can be applied to two integration levels. The first is to connect the simulation with the ERP. This enables testing the ERP and material flow. The second integration level is to connect with the PLC, which enables testing the PLC logic. The model can be used after commissioning for training and further development during operation [Strigl 2009]. When Virtual Commissioning is practically used, electrical, mechanical, and software departments can collaborate from early project phases on. Thus, planning and construction can be executed in parallel. This saves time during commissioning and enables earlier, faster ramp-ups. Sauer suggests using Virtual Commissioning also for production parallel real-time simulation [Sauer et al. 2010]. Further suggestions suppose applying Virtual Commissioning not only for pre-acceptance tests to improve software stability and minimise risks, but also for demonstration, training, customer support, system diagnosis and optimisation and other use cases [Quirós et al. 2016].

Virtual Commissioning includes the concrete program code, but therefore, it requires a certain effort to build it up. Modelling a complete production plant or network of plants with focus on the concrete control structure, requires high modelling effort. Blockwitz suggests two possibilities to reduce modelling costs for Virtual Commissioning: either multiple usage of one model along the design process or automatic model building [Blockwitz 2009].

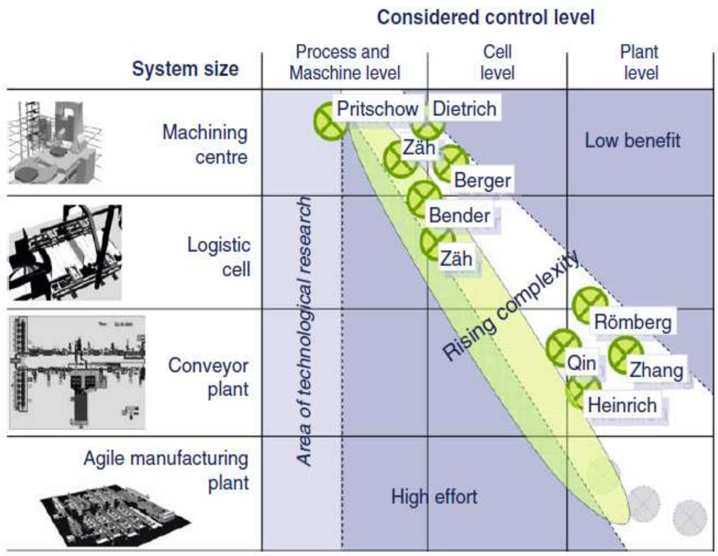


Figure 6: VC Approaches Related to Size and Level, Source [Reinhart and Wünsch 2007]

2.2.3 Discrete Event Simulation

Discrete event simulation is a test environment for “systems in which state variables changes only at a discrete set of points in time” [Banks et al. 2014], like material flow and process sequencing. The system is represented as a process or sequence, including delays, resource usage or waiting and queuing. Operations are modelled by start and end event, changes in between are not possible. Continuous time methods would allow changes during the operation [Borshchev 2013]. It is well established for early production planning phases and reordering sequence of an operating system when the software is not yet programmed, but the processes and sequences in general are already defined. Larger logistic and manufacturing structures like production lines or plants can be treated, because the logic is abstracted. As it is a common tool of Digital Factory, sequence simulation is widely used and well developed for simulation of larger scale production lines. For example, Plant Simulation is a standard tool for strategic optimisation as well as planning and control for existing or planned lines or plants or for re-use projects [Bangsow 2010].

Other than Virtual Commissioning, sequence simulation does not rely on the original program source code of the automation, but the logic is abstracted in the simulation model [Bangsow 2011]. Therefore modelling effort is reduced, because not every automation detail is displayed.

This makes it easier to use in early planning phases, when the control logic is not yet completed or the processes still have to be agreed. However, the program itself with all its influences cannot be tested.

2.3 Factory Planning

Production is the transformation of input (including material, machines, human, information, and capital) into output products and services. The transformation demands product design, production planning, production control, and maintenance. Manufacturing processes can be arranged to different processes [Dubbel 2014]:

- Primary forming process, e.g. foundry
- Forming process, e.g. body in white
- Cutting process, e.g. machining
- Joining process
- Special technologies, like gear cutting, micro-technology or rapid prototyping

Finished parts can be assembled to a complete product.

Project management for car development processes can be divided into [VDA 2003]:

- Project request
- Release for basic engineering of product and process
- Release for detailed engineering of the product
- Release for detailed planning of the production process
- Release for purchase and manufacturing of the production facilities
- Release for serial production (start of production SOP)
- Finish on targeted output

Schenk et al. define five phases of factory planning. These phases are further divided into three steps each [Schenk et al. 2014]:

Table 3: Planning Phases Following the Factory's Lifecycle, Source: [Schenk et al 2014]

Phases of factory lifecycle	**Planning steps**
Development	• Pre-planning • Main planning • Detailed planning
Build-up	• Realisation planning • Inspection planning • Commissioning planning
Ramp-up	• Ramp-up planning • Run-up planning • Normal operation planning
Operation	• Observation planning • Change planning • Adjustment planning
Dismounting	• Reconstruction planning • Shutdown planning • Recycling planning

Grundig divides the planning process into 6 planning phases [Grundig 2015]:

1. Target planning
2. Pre-planning
3. Basic planning
4. Detailed planning
5. Conduction planning
6. Conduction

Planning activities in this context are initialisation, analysis, concept, synthesis and integration.

The oldest and best-known planning method for system engineering is the waterfall model [Haberfellner et al 2015]. The relevant project phases are clearly separated and strictly consecutive [Burghardt 2012]. For example, purchase must be finished before construction can follow, which leads to commissioning etc. The V-Model describes software development in a technical and functional sight [Bröhl and Dröschel 1993]. The spiral model, an iterative prototype model, was suggested as an alternative to the waterfall model [Boehm 1988].

In IT development processes, agile planning is an increasingly used alternative to waterfall model in conventional planning processes nowadays. It is regularly used for IT projects. The advantage of this project process is that amendments or additional ideas can easily be integrated also later during the project [Röpstorff and Wiechmann 2012], [Wolf 2012]. For example, the scrum method no longer splits the process into planning phases, but the complete collection of tasks, the backlog, is graduated into sprints of approximately two to four weeks. In this time, the team agrees about a number of tasks to work on, as many items as they can assumable finish within one sprint. Developer work on the issues, the Product Owner represents the customer interests and the Scrum Master helps to solve impediments [Schmidt 2016].

2.4 Product and Production Planning

One major aspect of digitalisation is to process an abundance of data and information with best-possible benefit. Comprehensive databases are fed continuously with data from different sources and project phases. In reverse, applications can use it for various processes and feedback additional information to complete the dataset further. Product and production design can be set up as an integrated engineering process [Zafirov 2017]. Approaches to develop a coherent planning system for both product design and production planning started with a selection of CAx tools for computer aided engineering processed and continued with Computer Integrated Manufacturing CIM. Digital Factory linked digital tools for the planning process to one coherent database and Digital Twin approaches close the loop between construction and operation of production lines.

Consecutive data acquisition, storage and processing in manufacturing are a well-discussed topic in product and production planning. CAx systems integrate computer assistance in product development processes. Starting with computer aided design CAD and adding further planning and operation functions in Computer Integrated Manufacturing CIM, the tendency was to consolidate all available construction data in one data storage with shared user interfaces. A range of CAx methods are merged to an overall factory-planning database. Computer Integrated Manufacturing CIM aimed at continuous information connection especially in production [Bracht et al. 2018]. Product Lifecycle Management PLM and Product Data Management PDM combine various purposes of a product lifecycle in one consecutive tool [Vajna et al. 2018]. A combination of PLM with Manufacturing Execution System MES could synchronise product design and manufacturing [Antonio 2017].

Digital Factory provides a comprehensive database for planning and construction data, including various models, methods and tools related to production planning [VDI 4499]. Digital Factory has its origin in mechanical engineering. Electrical equipment is included for a mechatronic approach. Extending Digital Factory to IT systems and simulation prepares production planning for Industry 4.0. The Fraunhofer institute expects complete integration of MES system into Digital Factory in order to connect production and planning [Fraunhofer 2009]. Thus, early planning processes will be enriched with information, requirements and experience from production automation and operation IT. Optimising workflow, plant, line and process simulation using discrete event simulation as well as manufacturing tests with NC, robot and PLC simulation can be included in Digital Factory [Kühn 2006]. VDI norm 4499 includes simulation as standard method of Digital Factory [Wenzel 2010], [VDI 4499].

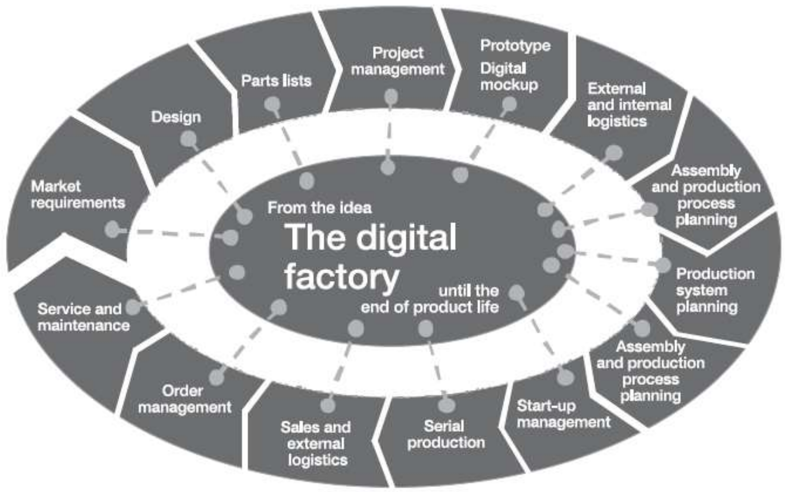


Figure 7: Holistic Production Planning with Digital Factory, Source: [VDI 4499]

Construction databases are often related to planning and early operation phases. Extended use for operation after commissioning allows feedback to planning and provides a holistic, comprehensive planning process. However, the gap between planning and operation including their IT systems closes merely slowly [Kühn 2006], [Sauer et al. 2010], [Schenk et al. 2014].

Related to digitalisation, concepts of continuous data acquisition, processing and storage are known as Digital Twin or Digital Shadow. Digital Twin mirrors a production line throughout the process from engineering onwards to operation. Existing data are complemented by sensor data. Thus, they form the digital twin [Mayer and Mieschner 2017]. Digital Shadow is a sufficiently exact model of processes, information and data of a company [Schuh et al. 2016]. Manufacturing simulation models can be used as digital shadows, running parallel to production processes [Mayer and Mieschner 2017].

2.5 Evaluation of Production Systems

Main task for this thesis is the evaluation and calculation of benefits and costs for smart production equipment. For production organisation in workshop, line or just-in-time production, calculation methods for scheduling and sequencing of orders and processes are well established [Curry and Feldmann 2011], [Fandel et al 2011], [Günther and Tempelmeier 2016], [Jacobs et al. 2011]. Scientific management was introduced by Taylor when he realised that no suitable measure is in use to evaluate business figures on a mathematic or scientific level [Taylor 1911]. Operations research was first developed by British army forces during World War II to develop highly sophisticated measures in military operations and logistics. It soon was applied for business operation. Business intelligence includes methods to optimise processes. Operations research provides mathematical methods to identify optimal solutions for decision processes [Bonart and Bär 2018].

Calculation methods for economic systems are established in cost calculation theories [Coenenberg et al. 2012], strategic management [Müller-Stewens and Lechner 2016], or operations research [Hillier and Liebermann 2015] or more specific for production and services operations management [Thonemann 2015]. Business processes can be evaluated scientifically, which includes interviews, statistical data analysis or structured observations [Bryman and Bell 2015]. Lean management has a focus on waste reduction and efficient processes. Organisation is optimised according to principles of flow, tact, pull and perfection. Targets are quality, delivery time and cost-efficiency [Bertagnolli 2018]. Based on common production targets, production planning and control optimises supply and delivery, process sequences and order scheduling [Deif and ElMaraghy 2009], [Lödding 2008], [Pinedo 2009], [Schuh and Stich 2012]. A number of optimisation methods are common for mathematically described constrains [Papageorgiou 2012], [Williams 2013] or mathematic models can be set up [Hedtstück 2013], [Korte and Vygen 2012], [Train 2009]. Operations Strategy defines the Value as a combination of Capabilities (actual and desired), Assets (sizing, timing, type and location) and Processes (in supply, technology, demand, innovation and risk). These four entities lead to the VCAP method: $V = C \times (A + P)$ [Mieghem and Allon 2015].

Calculation methods for flexible manufacturing systems FMS evaluate order sequences, production time and costs [Tempelmeier and Kuhn 1993], [Tetzlaff 1990]. Supply chain management analysis processes in relation to logistics concern [Stadtler et al. 2015]. With real-time production data processing, the recent state of machines and logistics can be included to adjust production better to actual circumstances. Processes can be continuously measured and optimised by advanced planning systems (APS). APS schedule processes, for example in an ERP system and measure, control and optimise production figures [Corsten and Gössinger 2016].

Methods for improved processes and productivity are manifold. 5-S-method concentrates on clean and structured workplaces to reduce search and preparation times. ABC and XYZ analysis help to concentrate on either the most effective or the cheapest available tasks. Lean production focuses on waste limitation. Balanced scorecard quantifies strategic company's targets. Continuous improvement processes, as the name suggests, drives improvements with a continuous workshop circle of plan, check, act and do. The Ishikawa diagram unveils conditions, causes and problems for observed processes or systems. A SWOT analysis evaluates strengths and weak points of an enterprise or department. Total productive maintenance TPM aims at systematically improvement of machine efficiency and availability. Other methods beyond these selections are also common [REFA 2011]. Previously described methods are a selection. Various solutions beyond are common as well.

3. State of the Art

3.1 History of Technological Development

Ian Morris evaluated the development in human society and rated technological improvement beginning 14.000 years before Christ [Morris 2010]. Main aspects will be summed up in this chapter. Innovation and development continued steadily on low rate early in humankind, but accelerated during the last decades with Industrial Revolution. Technological development improved life quality during the past centuries.

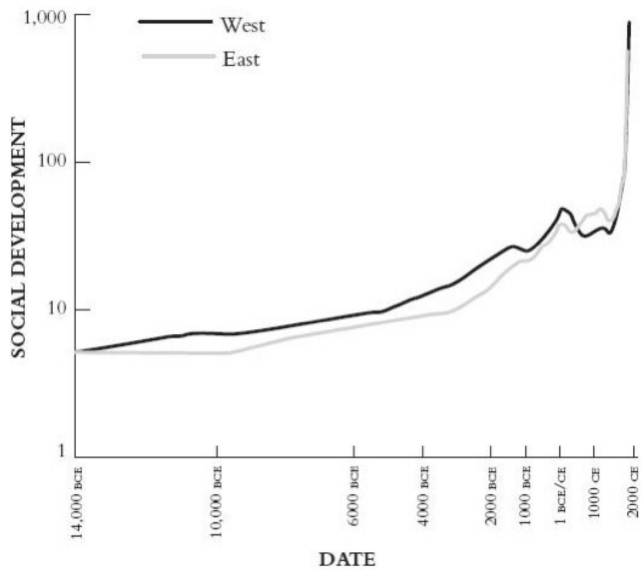


Figure 8: Growth of Social Development on Long-Linear Scale, Source: [Morris 2010].

Early human civilisation improved living standard by inventing better methods for daily services and businesses, use of fire, early tools, the development of the wheel and usage of native power supply. Improvement continued with mechanical and hydrodynamic drives, new material and processes. However, until the 17th or 18th century, technological development kept steady, but not as rapid as in the following centuries of Industrial Revolution.

Technological development accelerated in 18th century's Industrial Revolution with James Watt's invention of the steam engine in Birmingham. The west midlands became the centre of England's heavy industry and developed rapidly to a high-performance industrial hub. Starting with the invention of the steam engine, centralised energy supply enabled industrial processes and the start of capitalism. Steam power extended the availability of power from human or animal force to larger and flexibly adjustable scale and made it available nearly unlimited. Mass production and division of labour accelerated technological development within the following decades and centuries. Masses of workers were employed in factories. Compared to earlier innovations, the incubation time between Watt's experiments and following innovations that changed daily life further, was with only some decades rather short. The first steam engine had only poor efficiency, but improved rapidly. A huge range of improvements, related to this early innovation, followed. These inventions spread at the beginning of the 20th century over the world. Earlier inventions needed decades and centuries to be fully integrated. Compared to previous inventions, the incubation time between Watt's experiments and follow-up innovations that changed daily life, was with only some decades quite short.

Industrial revolution can be seen as the cradle of modern industry. Mass production and division of labour accelerated process efficiency within the following decades and centuries. Frederick Taylor established scientific methods based on mathematical evaluation of production processes. He split complex processes into numerous tiny tasks that a human can quickly adopt and improve [Taylor 1911]. Thus, labour efficiency improved rapidly. The labour for the single worker reduced to repetitive tasks at the conveyor belt, which Taylor strived to optimise mathematically.

Second Industrial Revolution was the development of electrical power supply at the beginning of the 20th century. Mechanical power is converted to electrical power, which can be distributed easier. Steam engines supplied a central force that drives a central shaft to which a range of weaving looms or other machines were coupled. However, the length of the driving axis is limited and far away located energy user could not be supplied. Electricity instead could be transferred to far distanced production sites. This made power available nearly without limits in terms of scale and location. It is limited by economic reasoning. Work was no longer relying on being placed close to the power supply, but the processes could be spread and sequence and locations of machines were independent. With better electrical supply, electrical machines became more common. Radio, communication technology and computers emerged. Electrification brought power to remote places. By empowering households, electricity improved daily life. Amenities that are standard today, developed in those days, such as electrical light, central heating and auxiliaries at work. After electricity distributed decentral power by using electrical grids, production automation could be developed, which improved efficiency and productivity in industrial processes. Sensors observed production and intervened, machines replaced hard and repetitive work, robots became common for pick and place tasks. Automation raised efficiency and productivity.

The third stage of Industrial Revolution is mainly related to automated processes. Machines and computers replaced routine jobs. In 1965, Gordon Moore, co-founder of Intel, found that the number of transistors in integrated circuits doubled every two years [Moore 1965]. In 1975, he predicted this regularity to continue for the next decade [Moore 1975]. This exponential growth indeed was stable and showed to stay accurate for decades. This law was later be adopted for quite a range of IT capacity content. With exponential growth, the abilities of computers exploded. Today it doubles estimated every 18 months. However, latest development shows further reduction, which seems to lead to kind of saturation point.

Three phases of Industrial Revolution can be distinguished:

- First Industrial Revolution: steam power enabling centralised power supply for mass production and factories work
- Second Industrial Revolution: electrification releases limits in power supply and distributed industrial settings
- Third Industrial Revolution: Automation replaces repetitive human labour by cheaper and precise machines

The now discussed Fourth Industrial Revolution is related to digital content, mass data processing and smart algorithms.

Other numberings are also common as well, counting electrification as the second phase and either include or not consider automation. Brynjolfsson describes digitalisation as second machine age [Brynjolfsson 2016]. To understand the phrase "Fourth Industrial Revolution", the above described numbering is more suitable.

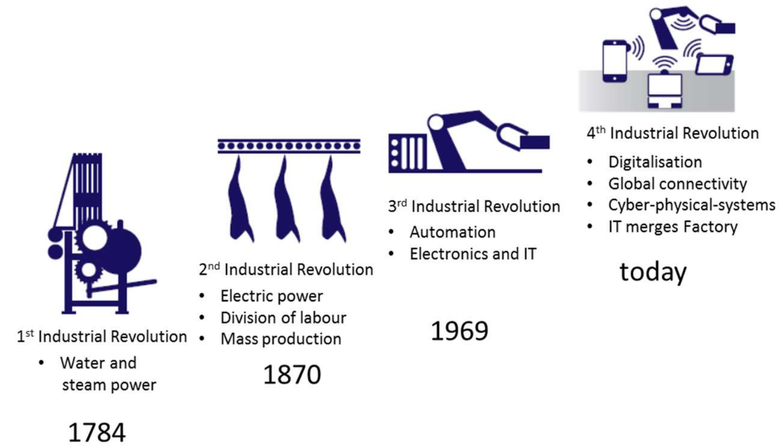


Figure 9: Industrial Revolution - Development Steps, Source: [acatec 2013].

Due to the abundance of data and modern data processing like artificial intelligence and big data analytics, the awareness of industrial processes and the connected environment changes. This should fit to future requirements.

3.2 Demands and Requirements in Producing Industries

Companies are challenged for quite a range of reasons. Markets are changing rapidly and developments are expected to continue and even accelerate further. Interconnected factories can share resources, therefore reduce installation cost. Major influences are volatile and globally connected markets, emerging new products and services, individually customised goods, sustainability, efficiency requirements and security demands.

Some general requirements for production kept unchanged: Industry must deliver customer's requests for goods and services in proved quality to acceptable prices and enough to cover demands. However, industrial processes as well as production environment and conditions of order, offer and distribution changes. Companies are forced to refurbish processes and structures rapidly [ElMaraghy 2009a], [Schenk et al. 2014]. Factories must become rational, flexible, automated, segmented, lean, fractal and agile [Westkämper 2006]. IT structures and virtual content are in the focus for renovation. Digitalisation is said to offer necessary solutions for requirements of modern manufacturing. Product updates or new products and services can be provided quicker and in more variations [ElMaraghy and Wiendahl 2009]. The company that can adopt new products first is most likely to exclude other competitors from valuable markets [Brynjolfsson 2016]. Some of the major drivers for industrial digitalisation are summed up here. The list could be further completed, but it is limited to only some of the most important demands and requirements.

3.2.1 Volatile Markets

Changing environment and political or economic conditions demand alignment of traditional structures to new customs. Producing industries are forced to improve products and processes continuously to keep up with competitors and to adjust to changing markets, political requirements and customer demand [Huber 2018], [Kofler 2018], [Vajna et al. 2018]. The numbers of product variants will increase and lifecycle time will reduce [Kiefer et al. 2008]. There is a demand on flexibility and efficiency from changing markets, demanding globally operating production networks, highly individually customized products, sustainability and zero marginal cost production [Rifkin 2014]. Global and volatile markets require quick response and easy adjustability to unexpected new conditions [Vogel-Heuser 2013].

Markets are changing. The importance of heavy industry sector such as steel and coal has shrunk for decades. Many industrial fields got less lucrative. They reduce production volume or even face bankruptcy. Nowadays, major boom sectors are rather IT technology and services. To catch up with innovation centres in Silicon Valley or Asian competitors, IT competences are requested from industry. The demand for intelligent systems will force industry to transform their processes towards smart manufacturing. Missing this development would mean missing chances to prepare for the future. Similar transformation difficulties can be seen in the West Midlands in England or in the Ruhr Area in Germany, where the turnover to service sector at the end of coal and steel era was missed.

The new machine age offers many opportunities for IT companies and IT related supplier. New software solutions are highly attractive for a vast range of customers and a lot of money will change its owner. This brings fortune to IT industry and everyone who can offer smart new application. However, often the end-user is demanded with the complexity. Not all options enable appropriate advantages. The right balance between challenging new options and usability must be found. Smart production is widely considered as the new source of disruptive innovations to bring a new wave of investment to machine vendors. Productivity figures, however, do not show the expected positive influence. Some companies even turn away from high-tech solutions and regarding their uncomfortable lessons they had to learn would not try again too soon. Producing companies are reliant on stable and easy to use processes.

3.2.2 Globalisation

Some hundred years ago, oversee sales for example by shipping were expensive. Colonialisation and global trade extended markets to far away countries. Globalisation can be divided into three phases: colonisation, industrialisation and information. The process increased in the 1990s exponentially. It is a permanent process, based on society, economy, capital and technology. Complexity, dynamic and uncertainty increases [Mäder 2018].

Cheap labour force abroad enabled cost reduction. The emerging BRICS states – Brazil, Russia, India, China and South Africa - could produce with cheaper labour costs and lower taxes and their influence increases rapidly [Volberda et al. 2011]. Tendencies to produce and sell globally increased during the last centuries. This accelerated during the dotcom era in the 1990s and at the turn of the century with further distribution of information.

Due to digitalisation, the customer is better informed about the choices of the market [Günthner et al. 2012]. Customers are now able to compare goods globally with only a few clicks and can thus choose the best offer. Some decades ago, the customer could only buy locally in the surrounding shops within an acceptable distance. Globalisation increases competition between companies not only in a locally limited market. When markets went global, every supplier could feed the world with their products. It is an everything-or-nothing market, where one company gets nearly the whole market and the rest cannot compete. Even if an offer is only slightly better than the second best offer, other competitors will have far less chances to sell their products successfully. This makes it hard for other participant to join this market. The company that has the first breakthrough on innovation for a new product or service can lock up the market against other competitors when the producer can connect the product directly to the name of the company. This accumulate economic success with few and often single supplier. Therefore, it is important for a company to establish products quickly and publish them before other can join the market.

Globalisation enables trades across borders. Restrictions on information and distance no longer separate different markets strictly from one another. Markets shift to less pluralistic and demand-offer relation emphasise more the customers' demand than the production abilities of the supplying industries. Only the best or the first offer will be able to place orders. The second best offer might be only slightly less attractive, but as there is a better offer available and the customer have free access to all offers, no one might be willing to take the second best choice.

At the same time, it is getting harder today to predict promising markets. International markets are getting more volatile than ever. China's economy is slowing down unexpectedly. The same can be seen for other important markets in Asia or Latin America. Promising BRICS states are getting volatile. Growth figures were long expected continuous and stable for states in Asia, especially China and India, Russia and Latin-American with Brazil. Growth numbers have been far higher than in traditional markets in Europe or America. However, these growth numbers currently melt away. Markets in important countries like China or Latin America recently crumble down. The risk to fall after rises increases. Financial and economic crisis dismantled established businesses around the globe. Volatility increases in various markets.

Discussion on international trade came up not only in developing markets, but also in the old world. The UK decided to leave the European Union with all consequences for international trade. Right wing parties in Germany, the UK, France, the Netherlands and Austria increase their popularity and extend nationalism, which would also effect trade relations to other countries. The US shift towards protectionism and cut existing trade deals. All these tendencies could tear manufacturing networks apart when previously free trade is limited.

3.2.3 New Products, Processes and Services

New products and processes attract customer and increase sales figures. Faster product development keeps companies competitive in changing markets. New technologies in automotive industry change this sector far more than it did during the past half century [Sperling et al. 2018]. Powertrain prepares for alternative drive. The influence of e-mobility on other sectors – for example energy or housing – is tremendous and requires interconnected services that span branches. Autonomously driving, connected cars and car sharing also change the relations between automotive and other industrial sectors. New processes and services are nowadays introduced more regularly and driven by increased digitalisation [Reichenbach 2017].

Automotive technologies developed stably for decades. Outstanding changes are still expected in the upcoming years [Pernicka et al. 2016]. Autonomous drive, e-mobility, and connected cars will dramatically amend the sector and with it, their production processes [Rehme et al. 2018]. However, not only the markets demand changes, new players appear. Automotive market now spread to further industrial sectors. Apple, Google and German Mail develop electrical, autonomous cars and mobile services. In the future, it will be more important than ever to globally adjust manufacturing capacity, to split and spread the production chain.

New materials like carbon composites are already common sense in wide ranges of mass production and they will find further usages. New processes like rapid prototyping also emerged and they were established rapidly. The integration of new derivatives in manufacturing systems requires efforts in the development of production facilities, project management and commissioning. Manufacturing must quickly adjust to new and amended products, processes and forms of organisation. Products and services must be developed and adjusted during shorter time slots. With individual demands, production cannot form larger batches of the same part type. In the end, the products must be produced in the same amount and sequence in which they are being ordered. This would require a batch size of one. Marginal costs will therefore reduce to nearly zero. Industry must improve flexibility and transformation ability of production systems to support these needs. Individual products can be implemented in 3D printer. The origin of this method is in prototyping, as only few models are needed, but have to change the design more often. These requirements are expected to become common production situation soon. Customer require individual products and market restriction demands more flexible production in the network periphery. 3D printing enables individual products up to batch size 1.

The manufacturer who can first offer a new device will concentrate the market as described earlier. The others might have invested a lot, but if they are the second best offer, the customer will hardly come back to this second choice. The same is valid for other innovations, services and processes. In an interconnected, informed world, advertisement on new or further developed products spread faster than ever before. A new kind of competition comes up. New products are demanded more frequently and the duration of usage shrinks. The lifecycle of the products reduces. Product type variety increased enormously lately and is likely to continue. Nearly 90% of producing companies expect far more often new products integration [Spath et al. 2013]. New models shall draw customers away from competitors. This increases the varieties of the products and the complexity of manufacturing [Meichsner 2009]. Customers demand innovative and individual derivatives. The demand for individual products forces marginal costs to be reduced. Additional offers are expected more frequently, the lifecycle time for innovations is shorter and the timeline for new products to be brought to market is getting more restrictive. Ramp up time for manufacturing facilities and product series will shrink in order to reduce efforts and increase productivity.

In the aftermath of the economic crises 2008/09, uncertainties of markets made market participants more sensitive for the need of flexibility reserves. Flexible production combined with smart algorithms and connected information platforms is seen as a huge source of efficiency raise and cost reduction. If machines can flexibly be used for different purposes, production facilities can be shared, which saves investment and running costs for resources. Extended production data acquisition should enhance transparency of the processes and are necessary to develop efficient and sustainable processes.

On the other hand, there is a huge choice of newly developed smart IT systems addressing exactly these targets on efficiency and flexibility. This pushing factor of smart IT offers an increasing amount of data and improved, extended IT functions. Exponential growth in IT capacity demands quick adjustment and innovation implementation in production. Companies, which do not catch up with digitalisation trends today, will not be able to sell their products tomorrow. “If a product needs three months instead of nine months to get to full production capacity, this is available money for the company” [Reithofer 2002]. In general, there are new possibilities due to availability of data and IT methods. These opportunities must be used to adjust best to tightened requirements.

Property is more often shared by a group of users, often called shareconomy. Services can create additional value. Shared services extend usage and require connected systems. The most valuable brands gain value from digital content: Apple, Google, Microsoft and Facebook [Forbes 2018]. Digital content attracts different from concrete products [Drenth et al. 2017]. Gadgets and services extend companies value. With digital content and aftersales services, a new value chain is added.

3.2.4 Sustainability

Reduction of power supply, water consumption and improvement in waste treatment and recycling has become high priority topic during the last years [Neugebauer 2014]. Efficiency is highly required both for ecological and economic reasons [Müller et al. 2009]. Digitalisation supports new opportunities for improved sustainability. Sharing production resources is a possibility to increase efficiency. With smart grids and interconnected supplier and consumer, efficiency can be increased. Transparency is needed for enhanced efficiency. Key players like the USA and China have realised the necessity of changing economy due to ongoing pollution and shrinking commodity supply. However, the withdrawal of the USA emphasises under President Trump the volatility in political decision taking, especially related to sustainability and ecology.

3.2.5 Cyber Security

Risks for connected digital systems are rising rapidly due to dependence of computer usage and extended networks [Garfinkel and Richter Lipford 2014]. Not only malfunction and over-complex systems threaten production stability, but also hacker attacks, spoofing (IP, DNS or Web spoofing), sniffing, port scanning, denial of service attacks or skimming. With more influence from IT side on production outcome, functionality and reliability, the awareness for cyber security has to rise. IT security has to deal with high-volume, crucial data exchange, safe operation and violation and attack blockage. IT security has deals with unauthorised access on information and communication systems [Poguntke 2013].

Unsecure systems enable unauthorised personal to control them. Interconnected systems exchange important and sensitive production data. If these data streams are not secure, company’s information might leak. Trojans catch information and enable unauthorized persons to follow data transfer. Another problem might be that data are corrupted on their way through the internet. This could cause malfunction of the receiving communication partners. Network participants and smart devises might be misused for cybercrime.

Stuxnet is the most famous program that hacked a nuclear power plant and affected centrifuges to turn slower. Thus, the processes looked normal, but the products produced by the affected facilities were useless.

Security measure like access control, authentication, cryptology, firewalls and intrusion prevention systems [Poguntke 2013], [Stalling and Brown 2015] must increase in extended digital content. Information Security Management Systems ISMS can increase the safety level of a company and improve the awareness of the employees. First step towards a standardised security system is IEC62443 that is about to being developed [Junker 2015].

3.3 Digitalisation in Industry

This thesis will distinguish between two different strategies in production control: automation and digitalisation. These terms are not commonly agreed, but will be used in this thesis takes two separate phases in technological development apart.

The now valid phase of digitalisation is distinctively different from the previous stage of automation in the 19^{th} century. Third Industrial Revolution mainly dealt with automated reaction of an output actor as a reply to a sensor input signal change or input pattern. Tasks that have previously been done by human operator are transferred to computers. Machines can operate more precisely. Especially repetitive and precise tasks are adopted by machines [Schnieder 1999]. They can often operate cheaper, mostly in high-wage countries. In the first step, machines replaced simple routine jobs, which are easy to program and can be repeated in exactly the same sequence. The accuracy and process stability of machines led to further replacement of human labour. Target of automation efforts was the reduction of human labour costs and in the end totally deserted factories [Dostal et al. 1982]. The vision of deserted, self-operating systems is in discussion already for decades, but has hardly been completely fulfilled.

With digitalisation, also non-routine jobs are substituted by machines. Nowadays, machines are capable of even sophisticated and creative jobs. Computer beat world champions in chest and mimic human speech. They write newspaper articles or offer individual customer support in call centres. Daily tasks are shifted to machines that are using artificial intelligence and due to their calculation capacity get more successful. When it comes to calculation capacity of recurrent tasks, machines already score against human operator. Computer can calculate a huge amount of possibilities, handle probabilities and adjust known methods to a given tasks.

Technological differences between 3^{rd} and 4^{th} phase of Industrial Revolution are especially the sheer amount of big data streams to be processed, extended system autonomy of smart algorithms and intuitive, ubiquitous user interfaces. The Internet of Things IoT connects even simple devices like thermostat or lighting to the internet [Yoneda 2017]. Omnipresent devices interconnect and form a widely branched net of data processing spots. Machines receive awareness and learn from known situations and an abundance of saved data. They can react conditionally to a given situation and ponder actions related to their experience. For this state of machine intelligence, system analysis is getting demanding for programmers.

Different from previous technological development, digitalisation is to a certain degree driven by programs and projects from politics and science. Strategies guide companies and research to defined targets. They promote the integration of IT competences into high-level industry. Digitalisation therefore is not only driven by improved technology, but it is also formed by political intentions.

Table 4: Comparison Traditional and Smart Industry, Source: [ZVEI 2017]

Traditional industry	**Smart industry**
Big & heavy	Small & smart
Value added chain	Value added network
Industrial sector structures	Value added structures
Vertical	Horizontal
Central & hierarchical	Decentral & self-organised
Globalisation	Globalisation
Consortium driven	Consensus driven
Individual property	Sharing economy
Human **or** machine	Human **and** machine
Mass production	Production to batch size 1
Acceptance	Trust
Technology driven	Customer driven
Loyal customer	Volatile customer
Long lifecycles	Short lifecycles
Incremental change	Abrupt change
Complicated but plannable	Complex and unforeseeable
Low dynamic	High dynamic

3.4 Smart Systems

3.4.1 Definitions

Main aspect of digitalisation is the extended use of IT content [Sendler 2013]. However, due to the multiplicity of research and development approaches, an overall definition is not yet agreed [Antonio 2017], [Dörre 2016] and new approaches continue to occur. A range of publication deals with structuring the topic Industry 4.0. Partial solutions and work in progress for data acquisition, transports, processing and user interfaces have been proposed. Multiple approaches and solutions are summed up under this heading. Digitalisation for industry is highly branched with a wide choice of smart solutions, devices and services. Related terms are not clearly defined [Banholzer 2018], [Korfmacher 2018].

The smartness of smart devices like smart phone, smart grid or smart home is related to enhanced, digital content. This includes data acquisition, transformation or storage, algorithms based on artificial intelligent or big data analytics, sensors or human-machine-interfaces. The abundance of data suggests extended use for machine learning algorithms [Raschka and Mirjalili 2017]. Smart approaches, smart solutions or smart systems and structures are founded on digitalisation.

Smart Factory is mainly based on enhanced data and algorithms use in engineering process and digitalised production environment. In comparison to this, the term Digital Factory deals with continuous, integrated construction data, production and process databases and the link between different fields of production based on their data background. It was coined in the 1990s [Schenk et al. 2014]. It includes digital methods and tools along the whole lifecycle of a plant [VDI 4499], especially virtual reality and digital mock-up [Bracht et al. 2018].

Different approaches develop self-organised systems. Agile manufacturing extend lean production approach to react on customer demand with changing infrastructure, IT networks, cooperation with supplier and partners. Fractal factories reorganise on demand in a self-organised and self-optimised approach. Holon factories in Japan build up autonomous partial systems, but still in a hierarchic structure.

Industrial systems or production structures gain smartness in terms of digitalisation through extended use of information technology. Smart factories are intelligent systems that use digital content to improve production processes. This smartness is based on intelligent sensors, cyber-physical systems, ubiquitously available data of product or process and new methods of data evaluation, based on smart methods like artificial intelligence. Digitalisation for the industrial sector includes terms like Smart Factory or smart production. For this thesis, the terms smart systems, structures or approaches will be used to relate to digital context in production. A selection of smart manufacturing approaches will be described in the following chapter.

Digital content spreads throughout the data processing from the shopfloor to the user. For this work, it was helpful to distinguish between:

a) data acquisition, transmission and storage (smart devices, Internet of Things)
b) smart algorithm (artificial intelligence, big data analytics)
c) intuitive user interfaces (handheld devices, smartphones, tablet PCs)

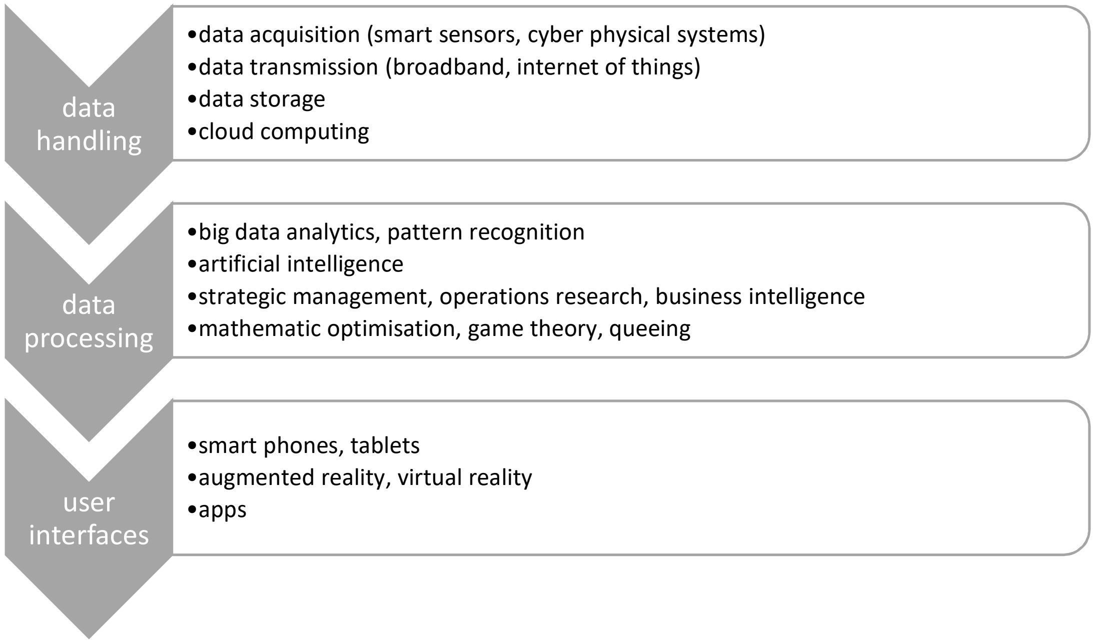


Figure 10: Components of Digitalisation: Input, Evaluation and Output

3.4.2 Smart Algorithms

An algorithm is a software code that is processed consecutively to find a solution for a given problem [Gumm and Sommer 2013]. Smart algorithms are on the rise in various fields of daily live. Successful solutions include artificial intelligence, pattern recognition and big data acquisition and evaluation. Smart control systems become widely distributed. They contain high-level control systems as well as multiple sensors, machines, robots, actors and smart devices like cyber-physical systems. Cyber-physical systems (CPS) are interconnected components that are linked with each other and via the internet with further services. They connect the physical world with information technology [Geisberger and Broy 2015]. Ordinary objects are individually addressable, they are connected and ether individually or as part of a larger group intelligent [Houbing et al. 2018]. Network participant interconnect with one another in the Internet of Things and share knowledge and resources, often a huge amount of data [Früh et al. 2018]. The Internet of Things links physical and virtual world. Machines and devices can connect highly branched, exchange data and build large networks of smart manufacturing facilities. Supply chain and logistics processes can exchange information, which improves their efficiency and flexibility. Distributed networks, connected computer networks and cloud solutions enable data storage and processes independently from the original location of its creation. This allows high availability of data processing in computing centres at low cost [Marinescu 2018].

Smart IT methods bare internal intelligence. Intelligence is the ability to understand unstructured information and correlations. Smart algorithms learn and adopt methods to a given situation. It contains the ability of awareness, judging, understand correlations and achieve understanding [Görz et al. 2014]. Machine learning can supervised, unsupervised and reinforced [Raschka and Mirjalili 2017]. Artificial neural network is closely related to natural brain structure. The neural network is composed by linked nodes or units. Activation propagates depending on the weight sum of the incoming signals [Russell and Norvig 2016]. Neuronal networks learn from pattern and can assign it to unknown pattern. Pattern recognition enables handling of far more situations, states and amounts of data than could be overseen by human operators. Data mining searches data for pattern that can be recognised, related and used for further processing. Search algorithms evaluate millions of possible solutions for suitability to a given problem and search for the best variety [Görz et al. 2014]. The best fit could either maximise, minimise or come closest to a targeted value. The easiest method is to just rush through all possible states and remember the best one. This easiest setting requires massive calculation power and it takes time. The calculation effort can be reduced with informed search, where only relevant paths are followed further. Thus, a bigger dataset can be tackled. However, this informed search must be prepared. The calculation result for an estimating or learning system such as artificial intelligence is depending on previous training phases [Russell and Norvig 2016].

Knowledge-based systems use artificial intelligence to support human decision making with machine knowledge [Akrerkar and Sajja 2010]. Automatic knowledge acquisition deals with acquisition without human describing and programming their knowledge. The machines evaluate engineering examples and solve new problems including learnt skills. Different methods are used to develop these methods. Rules can be created from data analysis using machine learning or data mining. Fuzzy logic deals with vague results [Görz et al. 2014]. Whereas common rule-based programmes react on input either 0 or 1, fuzzy logic can handle unclear states in between, which can be cluster to result classes [Kroll 2013]. A multi-agent system is a setting of various agents that react autonomously on their perception of the environment related to the agent's program to maximize its performance measure [Russell and Norvig 2016], [Pfeifer and Schmitt 2006]. It is based on artificial Intelligence and distributed computing [Hajduk et al. 2019]. Genetic algorithms are based on evolutionary methods. Successful settings can better continue to the next generation. Ambient intelligence can relate to distributed data.

Smart methods improve rapidly and new approaches come up continuously. The described methods are only an overview. Artificial intelligence, data mining and machine learning algorithms have shown astonishing improvement in recent years due to process adjustments.

3.4.3 Smart Factory

Event-discrete IT systems in manufacturing are widely rule-based coded [Tröster 2011], [Wellenreuther and Zastrow 2015]. The numbers of possible process states increase due to the amount of data and smart components. New systems often show better results, when autonomously operating machines and self-optimisation is included. Flexibility and adjustability to unforeseeable situations often cannot be programed with classical rule-based architecture. Learning and adjustment to new situations can be implemented easier with intelligent methods.

Production systems must be kept available at any time. Software must be able to tackle infinite state machines. For future systems, the amount of possibilities can be huge, too big to be evaluated completely. It is not possible to calculate all possibilities. Infinite state machines are often demanding to be overseen by a human operator due to their complexity. New methods for early approval of digital content must be implemented. At least the risks must become obvious and acceptable.

Artificial intelligence is harder to predict or to observe than rule-based programs. Optimisation with numeric methods and artificial intelligence is often not as transparent as rule-based process. Instead of programming the code by programmer, the system searches for an optimal solution, according to the given constrains. With artificial intelligence, a system improves with learning algorithms. By changing the setting of input and parameters, the correlated output variables are compared and the path of the best solutions is followed further. During a learning process, where thousands of situations are tried and compared in a structured manner, the system automatically finds its best performance.

The machine sets a decision in correspondence to previously learned situations or depending on the selected optimisation algorithm and recent system states. The result of this evaluation is set as the best result among a huge number of considered possible solutions. The human observer will hardly be able to calculate all relevant solutions. He therefore has to trust the computer’s decision. Artificial intelligence demand a good portion of trust in autonomously working structures, because the human operator can hardly emphasise with the algorithm and process [Gray 2017].

Computer scientists and engineers develop Smart Factory solutions in research centres for example at the University of Kaiserslautern [Kaiserslautern 2018] and in various companies and locations [OWL 2018]. Showrooms and research platforms are installed to develop Industry 4.0 and bring it to market and into the factories [BMBF 2017]. Key research topics are especially emergent software, user interfaces, for example with augmented reality to support operation staff or sensors for product data storage. Smart factories are often set up as modules that can be installed independently from other production facilities, following the principle of “plug and produce”. This is possible due to standard interfaces for manufacturing equipment, components and industrial information network [Pritschow et al. 2009]. Product and production facility interact as well. Information about the product is saved for example on RFID chips [Hupp 2017] or as a barcode or DMC code on the product. Thus, the part remembers completed processes and steps that are still to be done, including connected product and process data. With this knowledge, the part itself can decide which manufacturing facility to approach next. Traceability and recording of process data is essential for all production processes. For warranty reasons, all products must be tracked and quality data must be saved for years.

Production data are getting available ubiquitous. Thus, operation staff can interact better informed with the machines. They are aware about the situation on the shopfloor, of relevant devices and superior management systems. Connection to logistics and suppliers could soon be possible in real-time via the Internet of Things – a global network of interconnected smart devices. User interfaces like tablet PCs, wearables or virtual reality VR glasses [Jerald 2016] enable intuitive data access and processing.

Data from production will be used for advanced analytics and predictive maintenance. Examining huge amounts of data enables the vendor of the machines to analyse changing production environment and adjust offers accordingly to this. Artificial intelligence can be applied to support planning and programming [Brecher et al. 2015] or to improving production control with self-optimising systems [Lau 2010]

A lot of value will be established in services that enhance existing structures and systems. Remote support via internet as web services or Service-Oriented Architecture SOA keeps machine vendors in constant contact with their customers for further services. This enables continuous improvement of these products in aftersales services. Smart services connect to the Internet of Services. So-called shareconomy emphasises shared property [Hanna 2018]. Resources, cars, accommodation are shared, scheduled via the internet.

Smart transport and logistic systems are installed to enable flexible sequences, resource allocation and resource sharing. They do not add any value to the products, but they bare the ability to implement smart support functions. For example, resource sharing is only possible with advanced algorithms to analyse the recent and the targeted situation and to switch resources accordingly.

Decentral architecture allows re-use of known software components and distributed intelligence independent from the superior system. Pfeiffer and Schmitt suggest autonomous production cells as solution for over-engineered production lines, based on multi-agent systems [Pfeifer and Schmitt 2006]. It allows decentral control, self-organised production and open interfaces and standards. It enables the software designer to reassemble established partial processes to a whole system so that they do not need to start with the superior structure first. This allows turning planning processes into a piece-by-piece bottom-up approach. Decentralised software architecture allows re-use of known software components and distributed intelligence independent from the superior system. The software pieces or apps can be integrated to Windows based platform as for example Ziegler suggested it [Ziegler 2013].

With decentral data processing, questions arise on data security, safe and stable internet infrastructure, remote access and data distribution capacity on broadband. Different from a central architecture in which the program structure must spare time slots for the subordinate network participants to issue the correct sequence of the user program, decentralized software has an own independent run-time. Local error handling improves the availability of the whole system [Schloegl 2013].

The infrastructure must be improved for digitalisation. Broadband internet, data storage and processing service centres, cyber-physical systems and intelligent responding machines and robots are needed. Data transfer speed must be considered in process development projects, because time for database requests can limit process sequence and production output [Posse-Dölken 2006].

Agent-based systems enable distributed logic and interconnectivity. Agents plan future actions in foresight and the methods of communication is universal. A multi-agent system therefore interacts as a group of agents to fulfil complex tasks. These systems are said to reduce complexity as basic functions are encapsulated in an agent. This increases transparency. At the same time, flexibility and scalability are enabled, as the agents form standard elements and the complete system is safer against breakdown of single agents. Pfeiffer and Schmitt suggest autonomously operating production cells that are interconnected as decentralised multi agent system [Pfeifer and Schmitt 2006]. Agents have to negotiate to optimise the overall systems capability.

The IMS interregional project plant automation develops distributed systems establish decentral control systems in order to enable mass customisation [PABADIS 2004]. PABADIS tried to replace MES level between the devices and the ERP by a system of agents. However, agent-based systems often show less performance and slower reaction time. Software agents programed e.g. in C++, C# or Java enhance automation [Windmann et al. 2015]. Object oriented programming is regarded as standard program method for future production [Schuh et al. 2009].

Possel-Dölken suggests a multi-agent system, in which production facilities or components interact independently and decentralised. These agents are autonomous, interactive software processes that react on their environment and proactively initiate a behaviour strategy. Production processes are divided into agents, e.g., a product, a machine or a production order can be an agent. These agents contact each other and negotiate. The internal control structure is rule-based [Possel-Dölken 2006].

3.5 Targets for Digitalisation

Targets for digitalisation strategies are various and often confusing. Different companies evaluated the most common strategic targets.

Skilton sees digitalisation as a system of system integration, where closed and interconnected systems are linked [Skilton 2016]. Self-organised networks or components with encapsulated architecture, processes and internal policies are connected via internet. Main factor for digitalisation is therefore interconnectivity. Data combined with services and algorithms will expectedly spread further. With a more detailed knowledge about production processes, more influence can be implemented. For example, predictive maintenance relies on information about machine status, production times or surrounding circumstances. This process transparency allows additional services. However, this technology require complex transformation of the systems and bare risks for stable production [Jones 2017]. Industry 4.0 does not only improve common industrial targets, but it extends the abilities to flexible and changeable systems, which raises new economic opportunities [Bauernhansl 2016]. Miron expects various targets for the industrial Internet of Things: increased productivity and machine availability, less waste and better product quality or flexible usage of manufacturing equipment [Miron 2017]. Dombrowski and Richter expect efficiency to increase for a volatile, global production environment [Dombrowski and Richter 2016].

The association of electric industry ZVEI sees three central aspects for Industry 4.0 [ZVEI 2015a]:

1. Digitalisation and integration of value added chain
2. Digitalisation of product and service offer
3. New business models

Intention is to increase digital content to increase and integrate value and prepare new business models.

Several sources emphasise the important of transformability of producing industries and the positive influence, which Industry 4.0 can provide [acatech 2018], [Bauernhansl 2016], [Dücker et al. 2016], [Reinhart et al. 2013]. The Federal Ministry for Economic Affairs and Energy in Germany consider extended efficiency and additional business cases as main target [BMWi 2018a]. Westkämper found that 92% of the questioned companies regarded changeability as important or very important [Westkämper 2006].

Ernst & Young explores expectations that manufacturing companies have on Industry 4.0 [EY - 2016]: Most companies regard two objectives as the most important ones: production flexibility and faster reaction times on changing market situations. Other purposes seem not that relevant. Only a third regards cost reduction as important advantage. This shows that the ability of a company to react flexibly on changing markets and environment is considered far more important than raising cost efficiency. Two targets are seen as relevant by the majority of the surveyed companies: production flexibility and faster reaction times on changing environment. The picture of the most relevant targets seems clear: higher flexibility and quick reaction on changing customer and market requirements are the most often mentioned objectives. Most important achievements are expected in solutions of machine-to-machine communication and big data analytics. The biggest obstacles are initial investment costs and lack of highly qualified staff. Unclear economic benefit, deficit of IT-knowledge of the costumer and unclear business model are considered less problematic. Eighty percent of the surveyed companies regard Industry 4.0 as strategically important. However, economic benefits are among the less important arguments for digitalisation. Indeed, most companies expect costs during the transformation to increase first, before benefits pay. This can be seen in the fact that IT is often related to finance departments [Bitkom 2016].

McKinsey found, that opportunities are expected to increase, whereas expectations in financial aspects are less relevant [McKinsey 2017].Higher return on investment and lower investment are both in single or low double digit of expectation, whereas greater opportunities has the biggest share.

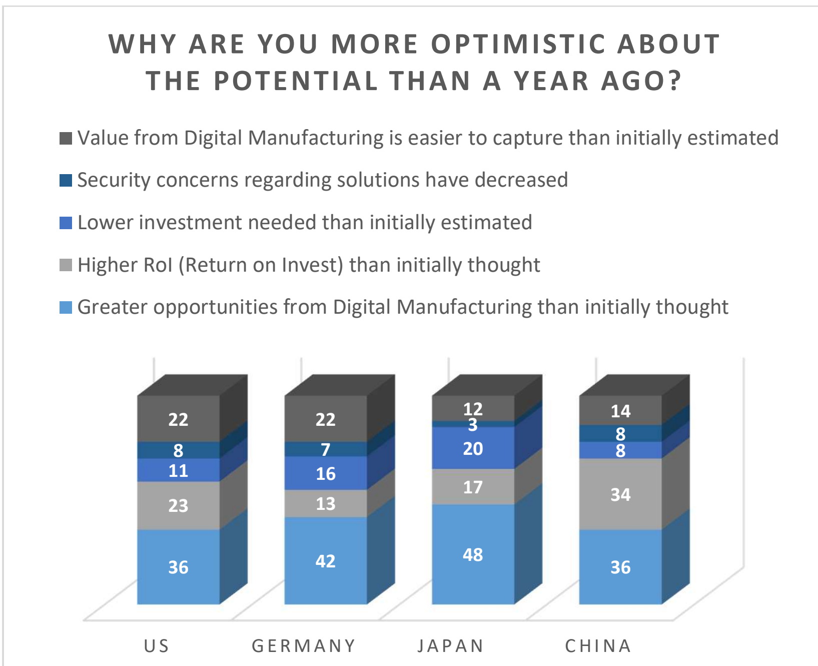


Figure 11: Study on Objectives for Digitalisation, Source [McKinsey 2017]

Another study describes three major strategic themes in the changes of European machinery industry [McKinsey 2016]:

1. Shifting growth patterns – geographically and along the value chain
2. Increasing pace of digitalisation – posing questions around the sustainability of traditional business models
3. Organisational change – to adapt to previously mentioned two changes and to volatile and competitive business environment

This suggests that common structures must be reviewed based on location, value chain, increasing digital content and volatile, competitive markets. Companies expect previously prevailing growth with the market and gains in market shares to shrink. They expect new markets and especially extended product portfolio to become more prosperous. Shift to (digital) services is expected to increase. Processes are not only optimised, they change [Huber 2018].

3.6 Digitalisation Strategies

3.6.1 Industry 4.0 in Germany

The term Industry 4.0 (often abbreviated as I4.0) or Fourth Industrial Revolution sums up technological projects, which connects information and communication technology with manufacturing excellence [acatech 2013], [Hannover Fair 2011], [Ramsauer 2013]. This vision was first launched at the Hannover Fair in Germany in 2011 [Weyer and Gorecky 2015] and is supported by strategic programs of Germany's federal government. German manufacturer have deep technical understanding of manufacturing processes and profound experience. They have a sophisticated system of technological standards, which on the other hand hinders quick launch for IT solutions [Schürmann 2016]. However, manufacturing knowledge merged with IT excellence might support German industry well. With Industry 4.0, high-tech expertise and product engineering can be kept in high wage companies [Ramsauer 2013].

The subjects for Industry 4.0 are versatile. Industry 4.0 is based on smart products, factories and services [Huber 2018]. Dynamic networks between plants and companies and large-scale logistics allow continuously process optimisation. Cyber physical systems interconnect to an Internet of Things, which melts physical and virtual world. Interface standards allow equipment, sensors and actors to communicate without lengthy installation and commissioning work, which is named plug-and-produce. Real-time processes link globally spread production facilities. A comprehensive database collects process data and provides information to various production related departments. Operation staff can receive more information and support from their machines or support systems. These new structures will allow manufacturer to produce individual products with an acceptable price level. Individual products will be likely to be produced efficiently. This will enable quick reactions on changing markets, and minimise external costs or delivery deficits. Machines and processes become transparent and optimise themselves, because they know their optimum or can calculate it. The product itself should save and proceed necessary information using RFID tags, QR or DMC codes [Kruse Brandão and Wolfram 2018] and feedback to the data backbone.

Various approaches are published. Industry 4.0 is a vast conglomerate of tendencies and terms, which is hard to summarise in clear lines. Efforts to form an agreed understanding and norms on Industry 4.0 are ongoing [Pfrommer et al. 2014]. National and international norming gathers relevant related norms and shows gaps for standardisation. In Germany DIN and DKE are involved [DIN 2016], [Hörcher 2015]. Tschöpe et al analysed the trend topic Industry 4.0 with database analysis. They found the most often used technologies in correlation with I4.0 [Tschöpe et al. 2015]. As there is no concrete standard or definition of Industry 4.0, this term is used in a wide range. This makes it harder to find an appropriate strategy for a concrete enterprise.

The changeover is expected between 2012 and 2025 [BMBF 2013]. Industry 4.0 is a vision of future production systems to structure discussion on future strategies. The Industry 4.0 association provides this vision as a sketch of a possible future industry [BMBF 2013]. It does not so much imply a detailed program, but gives a couple of useful strategic guidelines to display these complex visions and get it clearer. This helps to structure discussions. Nevertheless, Industry 4.0 is still in research, as standards and regulations are not yet fully defined and agreed. So far, Industry 4.0 is still only a vision for future manufacturing. Development projects are scheduled, implementation in productive industrial environment is not yet done [Kärcher 2014]. General target of Industry 4.0 is to improve manufacturing processes by extended usage of IT content.

3.6.2 International Digitalisation Strategies

Other countries have their own strategies to access the market for smart production. Their names hint at a development forecast between 2020 and 2025.

"Industrial Internet" in the USA focuses on product, production, and services. It drives industrial standards in healthcare, manufacturing, smart cities, transportation and energy. The Industrial Internet Consortium (IIC) develops and establishes standards in smart, interconnected manufacturing [IIC 2018]. IIoT, Industrial Internet of Things similarly to German Industry 4.0 promotes the combination of industrial processes with communication technology. It provides an overview on the marketplace of connected devices for different areas in industry. It promotes open standards on interoperability and connectivity levels. Similar to Industry 4.0, Industrial Internet accommodates a vast range of suggested solutions. Intelligent, self--regulating machines automatically adjust processes to prevent unscheduled breakdowns. Real-time data and intuitive handheld user interfaces support operation staff.

Emerging countries tend to apply new roles in industries as well. **"Made in China 2025"** is the corresponding strategy for China. Chinese economy struggles with severe overcapacity in heavy industry and cheap labour sector. So-called zombie-companies, especially in the coal and steel sector, have previously produced on state's order beyond market needs. With shrinking global growth and declining prices on the market, this causes continuous decline in China's growth figures, from double digit to less than 7%. To strengthen the manufacturing sector instead, "Made in China 2025" was issued by Chinese Ministry of Industry and Information Technology (MIIT) in 2015 in order to transform the country into a profitable high-technology industry. For the next two five-years-plans, main transformation is scheduled for 10 defined key industries, including robotics, IT, high-speed trains, aviation and aerospace. Several take-over of foreign company support the effort. The complete process is supposed to amend China into a world-leading industrial super power by 2049, which is the 100th anniversary of the People's Republic [Wübbeke et al 2016].

Frances **"Europe 2020"** is a strategy for research, technology transfer and innovation and aims at long-term and high-risk research in technological, economic and societal challenges of upcoming decades. Another French strategy is **"Industrie du Futur"**, launched in April 2015 supports development, implementation and standardisation of new production methods and digital technology. Therefore, the Alliance Industrie du Futur connects Industry, digital sector and universities [platform Industry 4.0 2016].

In 2009, Denmark launched the manufacturing collaboration **"Manufacturing 2025"**. Its purpose is to discuss and develop successful scenarios for future manufacturing´. Targets are especially international trade, customised solutions, services, but also disruptive technologies including Industry 4.0 [Johansen et al. 2010].

"Production Research 2020" in Sweden strives to improve manufacturing until 2020 by additional research in production engineering. It launches long-term plans for future challenges: globalisation and sustainability. Main tasks are sustainable and flexible production, the role of humans in production, innovative products and parallel product realisation, digital and knowledge-based production and globalisation [Narvinger 2008].

There are further strategies developed emerging. However, this selection should give an impression on recent developments; many of them are focused or at least related to enhanced IT content.

4. Deficits of Existing Solutions

Digitalisation efforts are increasing rapidly. A huge choice of smart solutions is now available, including intuitive user interfaces, sensor and actor applications or intelligent data processing. Costs and benefits, risks and opportunities of a given approach are often not discussed in depth nor are they put into relation to other solutions. Algorithms must proceed recorded data and the actors in the system must find actions appropriate for the recent request or situation. Cyber-physical systems alone cannot optimise production or logistic processes on their own; but improvement must be set up appropriately. Accurate prediction of relevant development is getting more sophisticated and demanding. The question how much benefit can actually be expected from digitalisation often remains unclear. To find the best-suitable system requires extensive structural and organisational refurbishment.

An evaluation system for Smart Factory approaches is highly recommended. This thesis suggests calculation and simulation methods to compare and rate smart solutions based on an analysis on benefits and risks of Industry 4.0 approaches. An exemplary system will be modelled and evaluated. Both will be discussed on suitability for the given purpose.

Simulation enables the user to test a production structure independent from the original system. Thus, engineering processes and planning projects can be improved in advance. Tests can be done before the production line is completed or when the line is not available for tests. Simulation can be realised without any risks of corrupting production data or breaking machines or other equipment. It is independent from the location and can be done in an office or workshop, where engineering and testing is cheaper, easier or more convenient. However, the effort to simulate different IT strategies can be massive, especially for the first integration of the necessary tools. Software and licenses must be purchased, user must be trained, required structures must be installed and data must be prepared.

Not only the simulation model itself must be prepared, but also an evaluation method is needed. A discussion on advantages of digitalisation must unveil, which benefits are expected. Then, it must be clarified, how systems can be set up to extract relevant production figures to increase these targets. Clear objectives and an overview on benefits and risks are still missing in the discussion on digitalisation. Various approaches can be found under the heading Industry 4.0. Concrete figures on the advantage are often hard to number. Objectives for digitalisation in producing industries are manifold and different user and companies will follow different targets.

5. Elaboration of the Task

Target for this thesis is the development of

- firstly a model to simulate relevant system context and
- secondly an evaluation method to compare and rate different solutions for smart manufacturing.

Both simulation tool and evaluation method will be discussed first. Then, an example for both is set up and finally in the concept description, both will be combined to a suitable process suggestion.

Table 5: Workflow Process Development for Simulation of Smart Factory.

Research Phase	**Chapter**	**Simulation**	**Evaluation**
Design study I	**Fundamentals**	Chapter 2.2 "Simulation for Production Software"	Chapter 2.5 "Evaluation of Production Systems"
Prescriptive study	**Introduction of the method**	Chapter 7 "Simulation Model Setup"	Chapter 6 "Performance Indicators for Digitalisation"
Design study II	**Verification**	Chapter 8 „Verification"	
	Validation	Chapter 9 „Validation"	
	Concept	Chapter 10 „Concept"	

With these two methodical components (simulation and evaluation) the user should be enabled to test smart production approaches detailed and with a clear focus on concrete purposes. Risks and disadvantages should become obvious and necessary amendments can be implemented early enough before the solution is activated.

At the beginning, performance figures for manufacturing systems must be defined. This includes a discussion on advantages of intelligent production structures. A simulation model suitable for Smart Factory approaches is set up, based on a concrete production system. The selected targets for smart production must be evaluated. The method should be open enough to adopt it to different objectives of smart production and different production systems.

For tests of Smart Factory solutions, large models must operate sufficiently. At the same time, the software logic must be modelled realistically to reproduce the system's behaviour of a smart IT solution adequately. A combination of the simulation task for large-scale production facilities, but detailed process expression and original source code must be found. Several simulation tools are commercially available and will be discussed for suitability. As described in the previous chapter 2.2 "*Simulation for Production Software*", there is already a range of simulation tools commercially available for production simulation. The best approach would be to use available tools and adjust them if necessary. With commercially available software tools, setup is comparatively easy, the support of the software provider is assured and experiences of other users can be included. If possible, established solutions should be chosen. A scheme for an exemplary simulation model should clarify, whether the system is sufficient and can be set up efficiently enough.

With this simulation model, scenarios can be tested and established. Evaluation methods for comparison and rating of different smart IT solutions must be prepared. Adjustment of input parameters allows scenario testing for different situations. By comparing performance indicator figures, optimisation can be done. Suitable comparison figures must describe advantages and risks of different solutions. An evaluation method for improvement of smart production structures should accompany planning and commissioning processes and can support optimisation later on during series production.

Deriving from the described fundamentals, the initial research questions in chapter 1.3 "*Objectives*" are enriched with the results from literature study and evaluation of state of technology. Therefore, the detailed research questions are defined.

1. Does a simulation model allow sufficient testing on smart production IT approaches and how can the model be set up?
    a. Which requirements are relevant for the model?
    b. How can a simulation method for digitalisation approaches be implemented and operated appropriately?
    c. How can evaluation be implemented during the planning process?
    d. To what extend and at what point of the planning process can smart production IT be compared and optimised best? Are there limits for this method?
2. How can smart production systems be evaluated and compared?
    a. What are the major objectives and requirements for future production systems?
    b. How can new production structures be compared and evaluated?
3. Which results can be derived from a simulation and evaluation method for Smart Factory approaches?
    a. Which results can be deduced from smart system evaluation?
    b. Do alternatives for simulation exist?
    c. Can correlations be found for digitalisation strategy?

6. Performance Indicators for Digitalisation

With appropriate parameter settings, production facilities can be compared and the best-performing solutions can be identified. Often even the target agreement discussion itself already helps the planning team to get a clearer picture on necessities and requirements. Optimisation routines can accompany the standard planning process. Specific performance indication figures enable qualified decisions on benefits and risks of smart production concepts. The defined performance indicators must be suitable to address the necessary developments for smart production.

General objectives for production can be separated in technical, economic, social or ecological figures [Corsten and Gössinger 2016]. Capacity, flexibility, stability and reliability are basic features of production systems [Härdler and Gonschorek 2016]. Main production targets are especially capacity to produce a certain amount of products in agreed quality and time and flexibility to produce the demanded amount and type of products [Corsten and Gössinger 2016].

At the beginning of a planning project, management, planning and production team define key figures to observe processes and to track the progress of a project. This ensures that operation staff will receive capable production lines, which meets the agreed target figures. Key performance figures in general include cost agreement, quality and timeline requirements [Hab and Wagner 2013]. These three expectations span a triangle of requirement; the requirements condition and violate each other [Castillo 2016]. Quality inspection is expensive and does not directly add value; it rather avoids losses. Fast production bares risks of quality defect and quick and sophisticated processes demand higher investment. Balancing the different objectives is required.

Economic targets are agreed early in the project in order to decide if a proposed project can be run profitably. Companies must operate cost-efficiently in order to make the necessary income. Cost calculation is widely established in management strategies. It leads operation and further development. Key figures are especially target price and costs per produced part, return on investment, profitability or productivity, machine costs and overall project costs. Time figures can be related to cycle time, throughput time, correlation of productive and failure time and mean time to repair. Quality is a key performance indicator to attract customers, but warranty concerns can also relate to costs as well as the company's reputation.

Highly automated manufacturing lines have been in discussion already for decades for the purpose of improved efficiency, reduced resources and personal demand, as described in chapter 3.3 "*Digitalisation in Industry*". Today, Industry 4.0 and related strategies puts these targets back on the agenda for better scheduling, transparency and especially quick response on changing markets. An overview on common literature is summed up in chapter 3.5 "*Targets for Digitalisation*". Targeted performance figures for digitalisation must be defined from this analysis.

Digitalisation costs and benefits are hard to calculate. This is a common problem in innovation management. A clear and widely agreed definition on content and purpose of digitalisation is hard to find [Gleich et al 2016]. Too many diverse solutions have been proposed lately so that the overview is blurred. Various papers concentrate on sorting solutions, approaches and techniques related to Industry 4.0 [DIN 2016], [Pfrommer et al. 2014], [Tschöpe et al. 2015], [ZVEI 2015b]. Many companies are still at the beginning of this development [Korfmacher 2018]. Independent from general production figures, questions about changed correlations of costs and benefits for digitalisation approaches remains unclear.

Not all performance figures are equally relevant for every company. Depending on the requirements, a test system must provide an accurate discussion and a valid data background for the considered situation. This chapter will discuss a selection of targets for smart factory approaches. The chosen performance indicators are capable to recommend suitable production systems for the digital era. There are various purposes for digitalisation. However, a couple of targets are valid for most companies and for various industrial sectors. The following chapters will introduce a general discussion for objective definition.

The preceding phase of automation had a focus on extended efficiency and reduction of human labour force. Machines replaced human operation staff if they are able to work more efficiently and precisely on repetitive tasks. Automation mainly deals with efficiency increase through replacement of repetitive jobs by machines, but it is limited by the system's complexity. Digitalisation deals more with additional usage for the now available abundance of data. Automotive, machinery and plant engineering benefit from real-time data, changeable production systems, interconnected facilities and intuitive user concepts [Bauer et al. 2014]. With digitalisation, the number of automated items spreads further, too, but furthermore, it includes additional new features. Therefore, it does not only continue the use of automated systems, but it strives for further objectives, based on supplementary benefits of big data acquisition and processing or smart and interconnected devices and services. Processes change with digitalisation [Huber 2018]. Additional benefits for digital processes are especially increased transparency and the ability to adjust production to changing markets, customer demands and environment. Efficiency can increase further, but additional targets complement it. Relevant developments are related to big data streams and intelligent algorithms anyway.

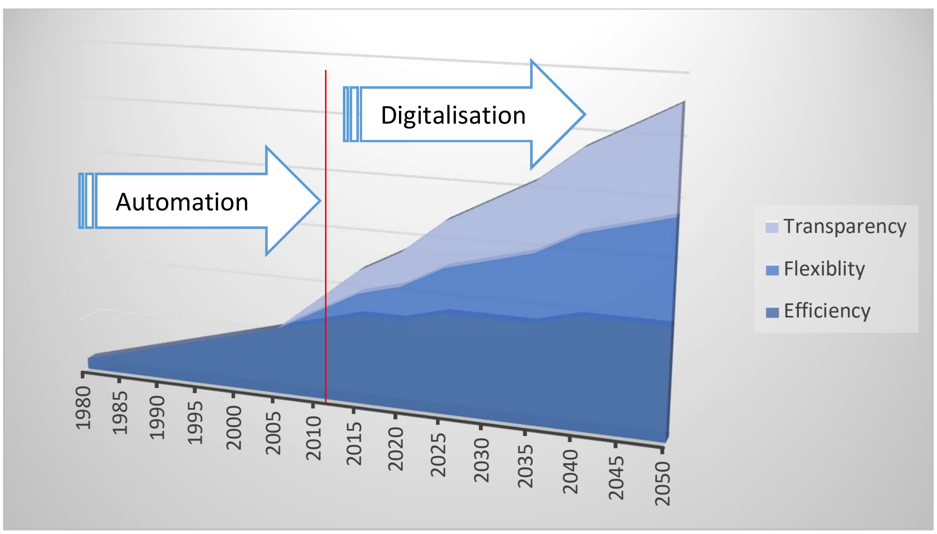


Figure 12: Automation and Digitalisation, Qualitative Sketch of Expected Course

Recent discussions showed that the ability to react quickly on changing environment becomes most crucial in the discussion about smart factories. Previously common manufacturing concepts and factory structures lock a lot of investment to manufacturing equipment and rely on high output. Target for the upcoming industrial revolution is the reduction of marginal cost to increase flexibility and changeability. Financial agreements are relevant for any project to insure that the development will pay. Economic aspects will therefore be discussed as well.

The abundance of data allows a better understanding in processes and their connection. Transparency can raise understanding about the processes. Thus, interdependent correlations can be found and used to improve processes. Therefore, transparency is another highly welcome and often mentioned target.

For this thesis, a selection of the expectedly most valuable figures will establish a performance measuring system. The performance indicators will therefore be:

1. Flexible and transformable production
2. Economic contribution
3. Transparency

Focus for this thesis is flexibility and transformability as it is the major objective for recent production systems and widely in discussion on the subject of digital content for manufacturing. It is also chosen for validation and verification of the suggested method. Economic contribution and transparency are briefly summed up and put into relation to digitalisation efforts. General performance figures are proposed that are commonly used.

Table 6: Detailed Objectives for Digitalisation

Flexibility / changeability	**Economic contribution**	**Transparency**
Real-time production	Productivity	Interconnect production facilities efficiently
Short-term production capacity reserve week to week	Efficiency	Evaluate production data, sensor signals and machine and equipment states
Quick response on changing markets	Throughput	User interfaces and social media

However, general project targets like agreed output, project timeline and budget must be met nonetheless. If these basic objects are missed, the general purposes for these projects get lost. Targets for digitalisation must provide additional benefits. Measures to observe and guarantee basic project targets are common and will not be discussed again in this thesis. The following chapters focus on the selected objectives of digitalisation.

6.1 Adjust to Changing Environment

Flexibility and transformability is a key target for producing industries. The production network must be able to amend operation quickly to changing markets and environment. In the aftermath of economic crisis 2008/2009, companies became aware that production volume must be more flexible to adapt. The more volatile a market is, the faster adjustable a production system must be, especially with low total production volume and a vast product variety. Legal restrictions, taxation and import/ export limitation demand local production. Single product lines are less complex compared to lines for various derivatives and therefore easier to install, use and maintain, but often, the local market does not yield enough volume to install several single product lines. Flexible lines must provide a growing variety of part types to keep product variety high. Manufacturers must prepare for customer markets and more individually customised products. Production must approach zero marginal costs to enable mass customisation.

There are different levels and purposes of changeability [Dashchenko 2006]:

- Changeover ability: Machine or workstation can perform operations of a known workpiece at any desired moment with minimal effort and delay
- Flexibility: Manufacturing or assembly system can switch with minimal effort and delay within a pre-defined set of workpieces by logically re-programming, re-routing and re-scheduling of the same system
- Re-Configurability: Tactical ability of an entire production or logistics area to switch with reasonably little time and effort to new – although similar – members of a pre-defined parts group or family by physically changing the structure of manufacturing processes, material flows and logistical functions including removal or adding of components
- Transformability: Tactical ability of an entire factory structure to switch to different product groups or families. This calls for structural interventions in the production and logistics systems, in the structure and process, and in the area of personnel
- Agility: Strategic ability of an entire company to respond to changing markets by opening up new markets, developing the desired products portfolio and services, and building necessary manufacturing capacity.

Many approaches limit to two features. Flexibility is the possibility to adjust production volume or product types in a defined range, for example, 10% difference in the projected production volume. Transformability is the ability to adjust completely new and unexpected situations, for example assembly of electrical engines with a production line, originally designed for combustion engine [ElMaraghy and Wiendahl 2009], [Stegmüller and Zürn 2017]. For this thesis, the two terms flexibility and transformability are sufficient to describe adjustment to changing surrounding and conditions.

6.1.1 Flexibility

Flexibility is the speed at which a system can react to changes [Maleki 1991]. It is a figure to explain if, to which scope and how quickly a production system can adjust to other production tasks. It is depending on previous information on environment, system and results of a certain action. Flexibility is a dynamic figure and reacts on actions of the past [Corsten and Gössinger 2016]. It is needed for amount, type and time [Behrbohm 1985].

Optimal flexibility is gained, when marginal benefits are equal to marginal costs [Corsten and Gössinger 2016].

Equation 1: Optima Flexibility

$$\frac{dB(fl)}{dfl} = \frac{dC(fl)}{dfl}$$

With

- *B(fl)* benefits of flexibility
- *fl* flexibility
- *C(fl)* cost of flexibility

Flexibility demand must match with the flexibility potential of the system. High demand of flexibility requires a high capability for flexibility and low demand of flexibility is best with a low potential of flexibility. Else, the solution will be either too flexible or inflexible. Both are inappropriate [Lunze 2016].

Table 7: Flexibility Demand and Potential

		Demand of Flexibility	
		Low	**High**
Potential of Flexibility	**Low**	Okay (simple system)	Inflexible
	High	Over-flexible	Okay (flexible system)

Costs for flexibility can be seen in [Lunze 2016]:

- Production facility
  - More locked investment
  - More expensive production costs
- Material
  - More storage costs
  - More purchase costs
- Staff
  - More staff
  - Higher qualified staff

Advantage of flexibility is the ability to react to changing demand, changing products and minimum lot sizes. Disadvantage is collateral complexity. Therefore, flexibility must fit to complexity. Grossmann suggests system definition by changeability and variety [Grossmann 1992]:

Table 8: Changeability Dynamic

		Changeability, dynamics	
		Low	**High**
Variety	**High**	Complicated system	Complex and complicated system
	Low	Simple system	Complex system

Simple systems have few elements, inter-dependencies and behaviour possibilities. Complicated systems have many elements and inter-dependencies; the system behaviour is deterministic. Complex systems have few elements and inter-dependencies, but a high number of behaviour possibilities. Complete controllability is not given for complex systems. Complex and complicated systems have many elements and inter-dependencies, and high changeability of system elements over the time.

Simple systems operate only few derivatives with always the same processes. The system gets more complicated, when more varieties are produced with the same production line. Sequencing derivatives require program planning and order management. The products must be allocated to the available resources appropriately. Complexity extends with more part types, type changes and varying production volume. Effort increases further if varieties, sequence and production volume are hard to predict. Sophisticated scheduling is needed. Fault and malfunctions are harder to detect and to restore in complicated systems.

Today, flexibility is mainly scheduled week by week, but is expected to rise for both short and long-term staff scheduling dramatically from now between 11% and 27% to a future level of flexibility of 44% to 60% [Spath et al. 2013]. Smart systems are expected to enable complex and complicated systems with self-optimisation and computational intelligence.

6.1.2 Transformability

Transformability is the ability to react to amendments that are not yet foreseeable at the time of construction. Nyhius et al. described transformability of a production system as the possibility to implement amendments of the system in a larger scale than originally defined as flexibility reserve [Nyhius et al. 2008]. Primary abilities that enable changeability are:

1. Universality
2. Mobility
3. Scalability
4. Modularity
5. Compatibility

Transformability demand accelerates due to economic requirements and changing customer habits. New products and processes, volatile markets and mass customisation require major adjustments in manufacturing structures that cannot be predicted during planning and commissioning of a plant. The mechanical components of production facilities have a lifetime duration of possibly 15 or 20 years. This span of time can hardly be overseen in advance. Digitalisation thus increases demand for transformable systems. Internally changed processes or new technologies and methods can furthermore influence the shape of a production line.

Criteria for the ability to individualise products are [Lindemann and Ponn 2004]:

- Functionality: different purposes for the same product
- Adjustability: individual features
- Emotional character: distinguish due to social status, image, individuality etc.
- Frequency of usage: product use regularly
- Complexity: only reasonable for more complex products
- Price segment: low-value products are harder to produce economically
- Manufacturability: production measures must be available
- Modulation: geometrical independences improve individualisation
- Market size and dynamic: more efficient when more customers require them

6.2 Economic Contribution

Economy has pushed towards efficiency rise for decades and centuries. It accelerated during Industrial Revolution with mass production, labour division and Taylorism. This reduced marginal costs for production. Capitalism continuously strives towards efficiency raise. The point of singularity for this development would be at zero marginal costs. At this point, further improvement is no longer possible. However, after centuries of rapid improvement in productivity, growth seems to settle in recent years.

Looking back over the last centuries, new technologies enhanced productivity. Harding illustrates this retrospectively with an example of Kansas cornfields: “A hundred years ago, an army of farmers toiled to produce 30 bushels an acre; now only a few hands are needed to produce 160 bushels from the same land.” [Harding 2014]. For 120 years, the output per head increased by about 2% steadily, but in recent years, this law seems to be expired. The same effect can be seen in industries around the globe, whether it is in developed countries like America, Japan or the European Union or in emerging markets such as China or Latin America. Other authors also describe this productivity paradox and wonder, if the digital revolution can accelerate economic growth.

When it comes to comparing economic systems, the first question aims at the contribution to growth and productivity. Several authors described the history of improving economics due to technological advantages, which suddenly declined during the last decade. Nobel Prize winner Robert Solow found that most of economic growth in the USA in the first half of the 20th century is related to technological development. 30 years later in 1987, he remarked, “You can see the computer age everywhere but in the productivity statistics” [Solow 1987].

Gordon also spotted this decline in productivity figure. In addition to that, he sees six headwinds in US economy that will devour the remaining growth. It could bring economy back to a growth rate of about 0.2%, as it was before 1700 [Gordon 2012]. This would reduce the development seen in the past decades to only a unique occurrence, which will not be repeated with machine intelligent, IT or internet applications.

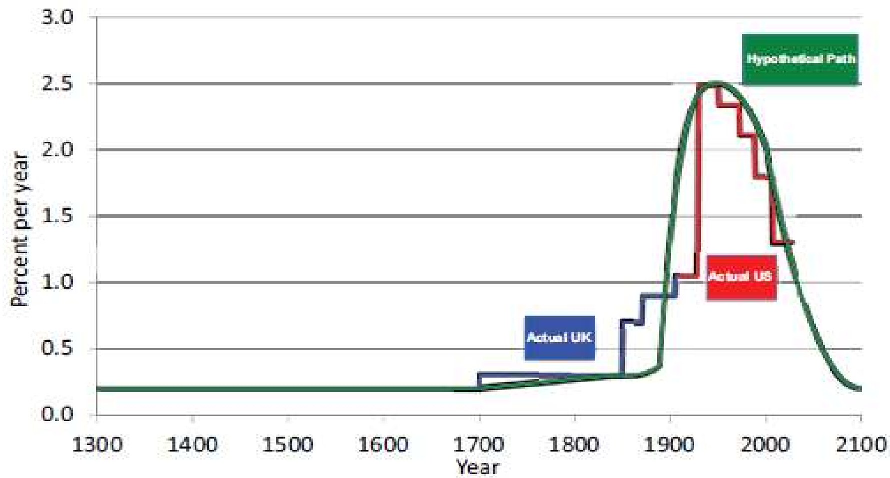


Figure 13: Growth in Real GDP per Capita 1300 - 2100, Source: [Gordon 2012]

Zero marginal costs are target for automated manufacturing. At this point, ongoing productivity gains can no longer contribute to cheaper products. However, the described productivity paradox hints at limits or saturation of digital systems. Productivity has not risen in any relation to the extension of smart devices, computers and intelligent algorithms. Development seems to have come to a hold. To continue growth, vendors can only cut their margin or offer new products and services. A major share of global turnover has already swept to digital content and services. It is quite likely, that the limit of capitalism with nowadays-available systems has already come close.

However, strive for efficiency accelerates with improved knowledge about the processes and continues with digitalisation, due to big data analytics, thus enhanced transparency and smart algorithms to react more intelligent on additional information.

6.2.1 Productivity

Productivity is a key performance figure and widely used in economic disputes. It can be evaluated in different levels of micro- and macro-economic system and it can be related to any input variable. In macro-economic context, national productivity can be defined.

Production figures can be calculated dynamically and partially [Corsten and Gössinger 2016]. Productivity P is average of the output compared to the input, related either to all input factors or only related to one, for example to the provided labour.

Equation 2: Productivity

$$P = \frac{x}{y}$$

Equation 3: Labour Productivity

$$P_{labour} = \frac{x}{r_{labour}}$$

Equation 4: Productivity Relate to any Input Factor r_i

$$P_i = \frac{x}{r_i}$$

With:

P – productivity
x – output
y – input
r_i – partial input factor i

Marginal productivity P_m describes how much productivity increases with one additionally produced product.

Equation 5: Marginal Productivity

$$P_m = \frac{\partial x}{\partial y}$$

Partial marginal productivity P_{mi} is the marginal change in productivity P related to an infinitesimal change of the input factor r_i :

Equation 6: Partial Marginal Productivity

$$P_{mi} = \frac{\partial x}{\partial r_i}$$

A discussion on productivity figures might enable wider overview on the impact.

Equation 7: Productivity

$$total\ factor\ productivity = \frac{output}{input}$$

For producing companies, productivity can be increased by extended output or reduction of input in terms of any relevant parameter. There is quite a range of measures possible to improve productivity.

One major factor to increase productivity is the efficiency of the processes.

6.2.2 Efficiency

Efficiency can be describes as [Kropik 2009]:

Equation 8: Efficiency

$$efficiency = \frac{planed\ cycle\ time * \sum_{Shift} parts}{T_{automatic\ mode}}$$

Efficiency increases with higher amounts of produced parts per time unit. It measures the ability to operate without waste and losses. Output per time should approach a maximum. Machines pay off when they are used appropriately. Machinery must be kept productive in order to return investment, because distortion from scheduled production volume raises costs. Unused time is waste and must be minimised. On the other hand, overtime shifts paid for additional work shifts are more expensive than regular shifts.

Resources must be available the whole operation time. Short-term breakdowns must be avoided; at least buffer for faulted or otherwise not available machines must be prepared for short-term interruptions or production must be bypassed on redundant, possibly manual stations. Long-term stoppages should be scheduled if possible early enough, so that all machines pause at the same time. At its optimum, the lines would run continuously.

Digitalisation is expected to increase sustainability and resource efficiency. Currently surplus facilities can be switched off or to energy save mode. This needs well-established algorithms to deselect machines and schedule consumers on the shop floor. Depending on information about supply chain, resource availability, customer demands, even weather forecasts, production schemes can be adjusted. The complete line sequence can be cut into operational pieces and fit together tightly to a gap-less time line of partial processes. Thus, resource is utilised at its maximum and production equipment can be spared. However, it will be necessary to enable the machines, manufacturing equipment and products to negotiate the best operation sequence. Efficiency indicators are for example hourly output, technical availability or Overall Equipment Effectiveness OEE.

6.3 Transparency

Flexibility requires transparency. Availability of all necessary information about the processes and their environment enables production staff to run their lines efficiently. For example, shortage of buy-in-parts for a predictable span of time, expected maintenance work and breakdowns or heavy weather influencing process, support or delivery could be foreseen in transparent systems. Machine learning has the ability to react to unknown situations, according to previously learned constraints. With more process data and better evaluation algorithms, different participants in the manufacturing process can proceed and share information throughout a wider process. Transparency and knowledge enables a system to predict upcoming situations, necessary maintenance or blockages. Optimal reaction must be induced to maximise output or set best production sequence. Energy can be scheduled and resource sharing could enable opportunities for major efficiency increase.

The amount of data increases rapidly. However, more data and interconnected systems increase complexity. New production processes therefore bare the risk of unforeseeable malfunctions and situations that are not covered in the control strategy. Operation staff needs confidence in their production facilities. They must be able to keep the overview over processes in order to run the lines stably. Big data streams allow enhanced knowledge about the monitored system. On the other hand, the sheer amount of data must be prepared and processed adequately. Manageability of knowledge, information and data must be increased. To ensure that a suggested solution is usable and understandable, transparency must be monitored.

The extent to which a system can get smart and interconnected without losing human control can be tested with a suitable simulation model, which describes the system behaviour. The operator must be able to understand and handle the system. One standard test to examine acceptance and operability of processes is the Task Load Index TLX, provided by NASA Ames Research Center [NASA 1986]. These tests evaluate perceived workload. Acceptance and system related performance can be rated for different solutions.

7. Simulation Model Setup

The following chapter describes an exemplary setting to simulate Smart Factory or Industry 4.0 approaches. Firstly, the requirements of a suitable modelling method must be defined. Next, the chosen example for a production system that is to be modelled is introduced and the workflow of the processes is described. Then a suitable starting point for simulation software must be chosen and a possible setup is established. The suitability for this case study is evaluated with a practical example.

7.1 Requirements

Digitalisation deals with intelligent, autonomously operating entities and with processing of big data. Especially the size and the content of the simulated system bare special demands for model building. For Smart Factory approaches, large models, covering several automation levels, are needed. At the same time, these models must contain real software logic.

The Internet of Things connects production facilities and plants to a global production network. This also includes production-related departments, like purchase, logistics or external partners such as vendors or customers. Smart Factories deal with larger scale, connected machines, plants and enterprises. A suitable model therefore must cover wide manufacturing structures and extended factory IT systems. The simulation model must be large enough to model not only one single machine or cell, but also a whole production line or a global network must be addressed adequately. With complex systems, not only separated applications or part systems must be tested, but its behaviour in relation to other participants of the network of machines, facilities, factories and supplier companies. The size for the simulation method must cover all relevant IT content for a particular smart solution.

Despite of the large scale to be covered, the control system's program code itself must be modelled in detail. Smart IT solutions require the real data structures to be tested effectively. Abstracting the logic is not satisfactory for numerous approaches. For example, artificial intelligence needs concrete learning patterns, big data analytics can only recognise pattern by using real data settings and agents' performance are highly relying on their surrounding and connected environment. Therefore, the system must display the same behaviour as the real production system. This covers a range of functions and function groups from fieldbus to EPR level. Cyber physical systems can only be tested when fieldbus level is simulated exactly. Detailed information on the logic of control devices can be analysed by using the exact PLC, NC, or robot software code.

Digitalisation strategy demands intensive and comprehensive testing. The system must be easy to adopt to different situations and scenarios. Amendments of the parameters must be set without major changes in the model and the status of the system and the simulation must be simple to retrace and operate. Different scenarios and solutions must be set easily to compare different approaches. The system must be stable and suitable for the observed parameter range. Relevant settings must correlate to the existing structure. Therefore, test staff must be able to change input parameter to check the system's response.

Output parameters and results must be accessible to be extracted and evaluated, so that the best constellation can be optimised. System states must therefore be accessible. This evaluation system must easily show relevant production data. Nevertheless, the system must still be easy to be set up. A visualisation helps the end-user to operate the model. Simulation models often include the rendered structure of the machines, which enables a human observer to understand the processes better. Visualisation undoubtedly improves the intuitive understanding. The acceptance for the model can be enhanced. Display of relevant parameters and user interfaces enable interactions. The simulation solution must fit to the IT landscape and the engineering processes of the company or department that uses it. The better it suits to the existing systems and processes, which the planning team already have, the easier is the installation, and confidence and acceptance can settle. This is important to motivate user to take advantage from newly developed methods. Finally, financial aspects must be considered as well, which means costs for equipment, implementation, licenses and training.

A suitable system must satisfy at least the following requirements:

1. The scale must be large enough to cover interconnected large-scale manufacturing facilities and possibly globally spread production networks
2. The model behaviour must correspond to the tested software
3. The model must be suitable for the given control hard- and software.
4. Realistic illustration of the machine and its processes improves user acceptance
5. Different scenarios must be set with an adjustable model.
6. Signals must be accessible for variation of input variables and evaluation of output data.
7. The modelling efforts must be at an acceptable level.
8. Easy usage
9. Cost efficiency (incl. hardware, software, licenses, training and support effort etc.)
10. Integration in planning process and IT landscape must be possible with acceptable efforts

With the following example, a Virtual Commissioning model will be enhanced in order to find suitable test settings for relevant smart manufacturing systems.

7.2 Exemplary Production System

The exemplary test system for this work is a machining line for engine production. Engine parts (crankcases, crankshafts, cylinder heads) are processed in a sequence of machining centres, assembly stations, honing machines and auxiliary operations like inspection, washing, impregnation, and rework stations. The parts follow the process sequence from machine to machine, beginning with the raw part loading until the finish part is unloaded and sent to logistics to provide to the customer, the engine assembly lines. Between the different cells, the parts are stored up in decoupling modules, where the parts can change the sequence. For example, urgent parts can overtake other parts with normal or low priority. In general, the parts are transported onwards to the next station on FIFO principle – First In – First Out. Inspection parts might be of higher priority, because their quality must be checked as soon as possible. Trial parts might be either of higher priority, when results are expected urgently or of lower priority, when production is more important and only spare time should be covered by these test parts. With a kind of high-rack warehouse, sequence change is enabled.

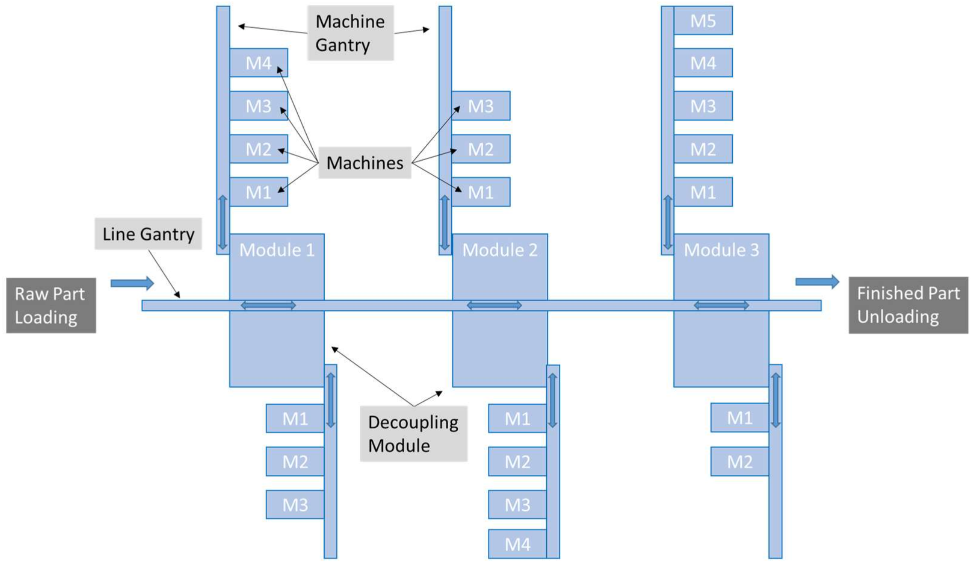


Figure 14: Line Concept

The parts move on to the following station on conveyor belts or with transport gantries. Machines are automatically loaded by loading gantries. For each part that arrives at the pick-up place of a cell, the transport system evaluates its type, where it comes from and which processes are needed next. All necessary production and process data for a particular part are saved on a database and can be downloaded when the part is about to being processed. The individual part number is read either from an RFID chip or from an etched data matrix code DMC. All machines send their recent status, whether they are in production mode and ready for loading and operating the next part or if they are faulted, maintenance or tool change is required next or other production relevant effects are valid.

With this information on product and facilities, the system evaluates the best available machine to be loaded next. The loading gantry picks up the part and loads the assigned machine. Therefore, part data are transferred to the machine. The machine checks whether it is either able to process this particular part and accepts the order or it denies the part, which requires a new order evaluation. An accepted part is transported to the machine together with the related part data. The machine processes this part according to the order, adds relevant process data to the part data set and releases the product, which then is transported to the next operation. The product data accompanies the part or they are sent to the database until the next process step is started. In relation to the processes, which have been done last, the part will approach different successive operations.

The described machining IT already includes quite intelligent functions. In common sequential lines, conveyor will move the product strictly from one station to the next when the current process is finished and the following station is empty and available. For machining, resource allocation is sophisticated, as there are several machines available for each cell. The cycle time is different for different cells. Multiple machining centres for the same task work in parallel in cells. Cells with longer cycle time require more machines than faster operating cells. The machines are decoupled and able to operate independently. Transport systems and decoupling or storage areas enable to re-assign the workpiece sequence. For this structure of machining centres, sophisticated resource allocation is necessary, as there are several machines available for each operation. A part can be produced on different machines and must therefore be assigned to the best available one.

This concept already contains a couple of features that fit to the vision of Industry 4.0. Product and machines negotiate to evaluate the best process sequence and the system allocates manufacturing resources in a decentralised routine. The cells contain several machines in parallel, which demands sophisticated resource allocation. Several functions that are in discussion for Smart Factory approaches are already in place here. Product and production facility communicate with one another. The sequence of the processes can be changed, with respect to the part status or machines' availability.

The example model simulates the routing of parts through the cell, including resource evaluation and the interface between machine and cell control. A standard cell for flexible production line in machining is chosen as example. The simulation starts when a workpiece is created on the incoming conveyor. The conveyor belt moves the workpiece to the pick-up place, where a part present sensor detects it and starts the next cycle. The mechanical construction of the line is eliminated for simulation. Therefore, the part detection sensor must be set by the behaviour model instead, because the real sensors and actors are omitted as well. A DMC camera is triggered by the part present sensor and it reads the data matrix code of the part. Instead of the DMC camera, an RFID chip could be read and written. This DMC code contains the individual number for this part and information about the part type. The complete data set of the part is stored in a database until the next process step calls for it. When the part has arrived at the pick-up place, the PCU of this station sends a request to an oracle database. The whole dataset is written into the receiving data block of the PLC. According to the workpiece data, the best available resource will be evaluated and the part will be sent to the allocated machine.

The parts are transported by a loading gantry. The gripper picks up a part and loads the machine. The processing of the part – drilling, cutting etc. - is not included in the simulation in depth, because this content is simulated separately and is not relevant for the sequencing, order- and resource-managing program. Therefore, the cycle inside the machining centre is abstracted: An adjustable cycle time runs and after this sequence is finished, process data are added to the part data. The product together with its dataset is sent back to the transport system to continue with the next process step.

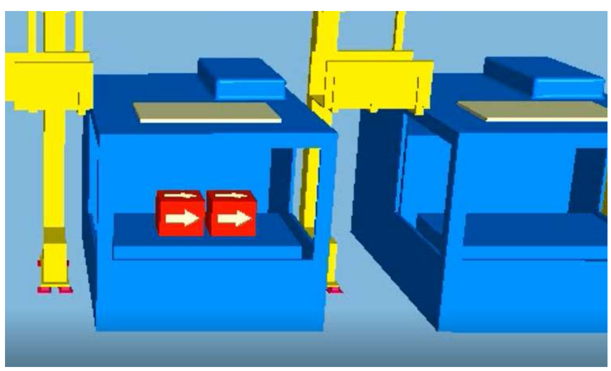


Figure 15: Cell Simulation, Modelled with RF::Suite and WinMOD

One repetitive partial system is a standard cell in the machining line. Start of the simulation is the incoming conveyor, set up as a part source. After finishing this cell, the part disappears in a simulated sink after it has left the machine again. Several cells can be lined up to larger production lines. Relevant part data can be edited in a behaviour model to create a certain type of workpieces with selected attributes. These part data must be available on the test oracle database. Signal changes from sensors must be set or reset by the behaviour model.

When the gripper picks up the part, the signal “no part in gripper” must be reset exactly in that moment when the gripper closes and a part would be present in the real plant. These signal changes are prepared in the behaviour model. All necessary processes are simulated accordingly.

Several data processing functions can thus be tested, evaluated, rated and further developed, for example order management, transport and logistic system or resource allocation. The simulation can be divided into repetitive processes, for which standard macros or library elements are developed:

- Standard input/ output data (safety doors, light curtains, fuses)
- Visualisation of moving components (Gripper, Conveyor, Hatches)
- Machine data
- Part data (part type, part status, next and previous operation)
- Tooling data
- Production orders

7.3 Simulation Software

Discrete event simulation enables tests on workflow, process sequence and logistics. The processes - especially in part transport and processing - are abstracted. This limits the modelling effort, but spares the concrete software code. A discrete event simulation model for the considered production systems is already available, but the program logic is not detailed enough for process description and evaluation as concrete as needed. For the described purpose of software logics evaluation, a model is necessary that allows drawing conclusion on NC, PLC, robots or Windows-PC level.

Virtual Commissioning as a test method for automation systems is based on the original source code. This is necessary to prove the correct logic of a cell or a machine program. However, the effort to set up the system is less convenient for larger sizes of manufacturing structures, larger than machines or cells. Therefore, the effort to set up Virtual Commissioning limits the economically acceptable model size. The larger the model, the more increases the effort for model building. The simulation setup must be done most efficiently to limit costs.

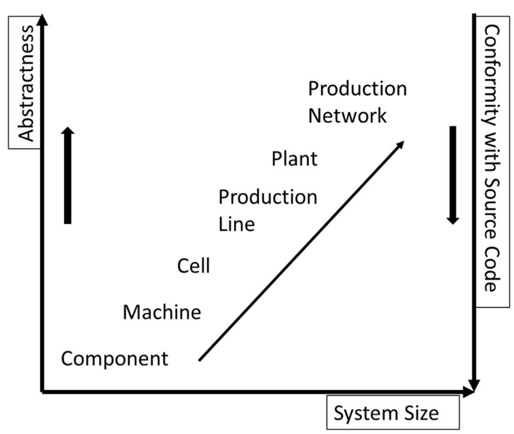


Figure 16: Correlation of System Size and Abstractness of Simulation

Virtual Commissioning is chosen as starting point for model building in the described context of large facilities, simulated closely related to the source code. A selection of software for Virtual Commissioning is already described previously in chapter 2.2 "*Simulation for Production Software*". As the target for this thesis is closely related to control systems, an automation-focused Virtual Commissioning tool is chosen. Various Virtual Commissioning software tools are suitable for the given task. WinMOD and RF::Suite show high performance and accuracy for automated production cells and are widely common. This solution is already established and released in the company as standard system for Virtual Commissioning and libraries are available. Performance and service are satisfactory and it is a cost-efficient solution for this project. Therefore, WinMOD with RF::Suite is chosen for behaviour modelling. In this project, WinMOD version 7.2.0.6 and SIMULATIONUnit version was 8.1.16 was used. For the visualisation, two different systems have been tested: RF::Suite from EKS InTec and Simline 8.0 by *Mewes & Partner.* Both systems are suitable. For this thesis, RF::Suite has been chosen.

The model is enlarged by the superior production planning software MES. Product, production and process information is saved and handled with the MES systems. The level above (ERP - Enterprise Resource Planning level) will not be modelled, as all relevant data are transferred from ERP to MES. MES is therefore sufficient for the given purpose. The MES system is simulated with a test system that runs on a virtual machine and a test database.

The simulation model therefore consists of:

- 3D visualisation: SGView by *EKS InTec*
- Behavior model: WinMOD by *Mewes & Partner*
- Control system: Sinumerik NCU720.3 by *Siemens*
- *MES*: PSS test server by *Siemens (a BMW specific system)*

Additional simulation models might be included as well to test further content, for example physical simulation or modelling the processes within the machine. The processes themselves are quite different related to a certain process, e.g. tooling data in machining or processing data (pressure, temperature) in foundry. For this work, machines have been considered as black boxes and processes within the machines have not been modelled, because order and resource allocations were in the focus. For the chosen functions that are to be improved – resource allocation, data processing, transport – a combination of Virtual Commissioning and test system of the MES is the least to be set up, but it should be sufficient.

One first example model is set up in chapter 7 "*Simulation Model Setup*". It is based on common simulation tools, as it is already common in production planning. This model must be extended to a complete test environment for larger manufacturing facilities. Possibilities to improve the model building process will be discussed in chapter 8 "Verification".

A flexible production line in machining has been chosen as a suitable example. The actual hardware equipment and the installed software of the manufacturing structure that is to be tested must be considered in the model. Not all tools provide the used control hard- and software. Especially for special purpose machines, the interfaces must be insured to work appropriately, because this might influence the accuracy of the simulation results a lot. The model must be validated carefully, especially when new, unknown or not common hardware devices or software tools are used.

The quality of simulation is highly relying on input data, construction and programming, as well as system definition. One regular problem is the costs to prepare models and the question if the benefits of Virtual Commissioning are in an acceptable relation to the efforts of model building. This limits the possible model size [Reinhart and Wünsch 2007].

Model building needs the following steps:

1. Hardware set up and connection
2. IP address setting
3. PCU, NCU basic set-up and software preparation
4. Adjust the system to simulation mode
5. Behaviour modelling
6. Visualisation

7.3.1 Topology and Hardware Setup

The described system is based on a CNC control system with Siemens Sinumerik 840d solution line components. This is a multi-core technology for demanding machining tasks for up to 32 axis, extendable by PLC axis or NCU link configuration. It is for general productive purposes set up with the control unit, a line module for power supply for drives and motor modules to control the drives. This hardware setting may be extended to further axis or channels with a NX component.

The NCU has several software layers, including a Numerical Control Kernel NCK with integrated PLC. It runs the NC program to drive the machine axes as well as the PLC program for the process logic and auxiliary functions. The basic software is saved on a compact flash card (CF card) and can be backed up as a .tgz file. This CF card contains a Linux operation system, SINUMERIK and NCK, PLC and Sinamics. The user programs of the NCU can be saved, transferred and loaded as archives. Archives save settings of NC, PLC and drives. The PCU is a Windows-based industrial PC. The Windows system is useful for the connection to other Windows-based software parts, for data exchange and user interfaces.

For Hardware-in-the-Loop Virtual Commissioning, real control hardware is requested for all software logic related components of the control system. For this project, this is the numerical control unit NCU and the PC unit PCU. HMI are needed for the user interface. Switches connect the components. The hardware for the test rack is reduced to only the control part without fieldbus components. All periphery devices are removed and simulated: Line module, motor modules and all sensors, motors etc. A thin control unit TCU, which is common to use the HMI without PCU, is not used here.

The system then consists of:

1. Numerical control unit Sinumerik NCU720.3 PN Version D
2. Windows based industrial PC PCU50.5-C, 1.86 GHz, 1024MB, WinXP Pro EmbSys
3. Operator Panelfront OP012, 12,1´TFT (800x600) Panel Series P1
4. Push button panel MPP483IEH-S44 panel 1, 24VDC, 35W, e-stop, EKS-Slot, feed rate
5. Scalance machine switch
6. Scalance company switch
7. SIMULATIONUnit PNIO

8. SIMULATIONUnit Profibus
9. Euchner EKS Switch

Furthermore, power supply for 24 V, plugs for 230V power socket, fuses, power supply, Ethernet and Profibus cables, keyboard and mouse. SIMULATIONUnit PNIO and SIMULATIONUnit Profibus emulate the removed Profinet and Profibus components, which communicate with the NCU.

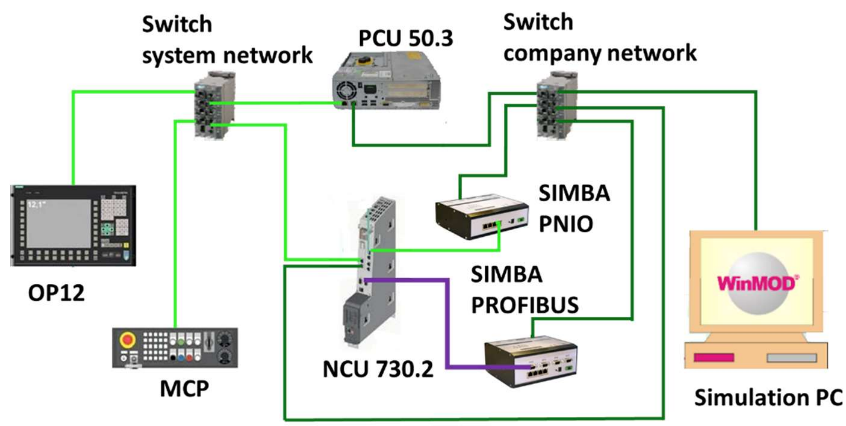


Figure 17: Hardware Set-Up for Test Environment

To use and set up the PLC and NC program and for system commissioning, Simatic manager is needed, as well as a variety of tools for Sinumerik. A field PG (programming device) with the following Siemens software packages are needed.

- Step 7 Simatic Manager, Sinumerik toolbox and all software packages that are used in the PLC for commissioning the PLC
- PCU ghost of the requested station
- HMI advanced as user interface and for commissioning NC and drives
- Support tools for Sinumerik such as Starter, ScanSL, WinSCP, NCConnectWizard

Some adjustments of the NCU must be done to keep the system running. Safety signals must be emulated, such as safety switches, manholes or hatches appropriately. The removed devices cannot send the necessary safety ready signals when the hardware is missing. Safety Integrated compares two signals for each safety device; one signal is set by the NC and another one by the PLC. The PLC signal can be emulated with SIMULATIONUnit, but NC signals must either be set by the simulation model or the safety check must be skipped to start the control unit. PLC input variables can be copied to the NC or the other way round. SPL check (safety check) can be forced to skip in the PLC and is forced SPL ready actively. Simulation axes must be set in the machine data.

7.3.2 SIMULATIONUnit

For Virtual Commissioning, the hardware is reduced to only the basic control units. Sensors, drives and others fieldbus components have been removed. Non-existing network participants must be emulated accordingly to the hardware configuration. The setting must be identical to the real system. SIMULATIONUnit by *Siemens* provides two functions: firstly, it emulates not connected fieldbus devices and secondly, it connects WinMOD with the control system. It emulate Profibus DP/PA or Profinet I/O devices (for example ET200S PN or CP1616) at one bus. It can simulate up to 32 channels in the same project at a time. Instead of SIMULATIONUnit, RF::FSBox by *EKS InTec* can be used as well. The system configuration of the PLC project must be imported to the project as:

- .cfg files for the hardware configuration
- .seq files for symbol list
- .dat files for SDB system data sets

7.3.3 Behaviour Model with WinMOD

For Virtual Commissioning, the mechanical equipment including sensors and actors is removed. The behaviour of the mechanical devices must be simulated. The PLC program can either run on real control hardware (Hardware-in-the-Loop) or it is emulated (Software-in-the-Loop). A combination of partly real and partly emulated control hardware (hybrid commissioning) is also known.

The software WinMOD developed by *Mewes & Partner* is a simulation tool used to simulate the behaviour of a real production system. WinMOD has to communicate with the real controller to establish a Hardware-in-the-Loop simulation. Therefore, the tool provides several configuration drivers to implement a signal exchange between the NC/ PLC controller and WinMOD. For the project described in this thesis, three drivers were used.

- A780 SIMBAPro: communication between SIMULATIONUnit and WinMOD
- A770 MPI S7: direct access to PLC memory, for example to read and write data blocks
- Y200 memory coupling: communication between WinMOD and 3D modesl in SGView

SIMULATIONUnit and WinMOD use the shared memory file “SIMBAkern.dll”. A780 driver is needed to couple WinMOD with SIMULATIONUnit. Direct connection between WinMOD and the PLC needs “A770 MPI S7” driver. The driver enables access to data blocks, memory bits and I/O addresses. This is needed to read position data from the axis and other commands from the NC – PLC interface signals. The position and movements for 3D visualisation is displayed related to data block entries. The WinMOD configuration “Y200 Memory Coupling“ is needed for signal exchange between WinMOD software and external applications to use WinMOD signals in other applications. In the described simulation environment, the external application in use is the software “RF::Suite” by *EKS Intec*, which allows modelling 3D visualisation of the mechanical equipment. The driver Y200 defines a shared memory that can be used by both WinMOD and the RF:: Suite’s visualisation tool “SGView”.

Signals from components, which are needed to run the PLC without faults, are set by the simulation model. All safety signals must be set, supply signals like drive ready, lubrication no fault, pneumatic or doors closed must be forced. Other signals are needed for the workflow, for example, for conveyor belts or part present sensors. All input and output signals are listed in the input/ output overview. Another overview gathers all signals that are needed for the visualisation, for example movements, valve open/ close, sensors and switches of gantry, gripper, conveyor belts and part exchanger. Status of machines and workpieces must be set and changed, which includes a couple of macros or library elements:

- Resource allocation
- Disabled machines
- Machine status acquisition
- Order management
- Workpiece data at the part source of the model
- Process and quality data

7.3.4 Visualisation with RF::Suite

The 3D kinematics software package RF::Suite is a toolbox for Virtual Commissioning preparation and simulation. This thesis uses the following components:

- RF::SGEdit
- RF::MAX
- RF::SGView
- RF::HMI

With SGEdit, all axis and positions of the construction data set are defined and arranged in a tree structure to allow independent movements and kinematic constrains. These PFB files are used in the simulation in RF::SGView. Workpieces are saved in separate files. The simulated processes, for example movement of axis or material flow, are set up in RF::MAX. The animated file can be operated with RF::SGView and RF::HMI.

7.3.5 Test Server

Manufacturing processes are managed with ERP and MES systems. Production program scheduling, gauge plans and tooling data are set in the ERP system, transferred to the MES system and further transmitted to relevant production systems for usage on the shopfloor. The machines are connected to company network and Oracle database in order to save relevant product data and to exchange and save process data.

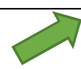
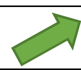
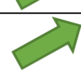
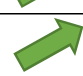
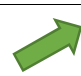
In the simulation environment, real production data are not accessible. The PCU needs information to run in automatic mode appropriately. A separate setting is necessary to avoid corrupting data that are relevant for legal concerns (warranty, product liability etc.). A separate Oracle database and a test server of the MES are used. Two different applications are available, one that runs on the PCU of the test rack and another one that runs on the simulation PC as a virtual machine. The test server provides resource management, work plans and workpiece data configuration.

8. Verification

The previously described model has been developed in order to enable development of smart production systems. Requirements for a suitable system have been summed up in chapter 7.1 "*Requirements*". The method should be suitable to test the abilities and risks of new manufacturing software solutions. The model must be large enough to cover large-scale manufacturing lines. Available simulation tools should be used and adjusted to the special needs of future systems, but not more than urgently necessary to keep system and integration costs at an acceptable limit. Other requests are rather general for any simulation project, like cost efficiency and good usability. All requirements must be met to an acceptable extend.

A starting point that fits best to the defined requirements was suggested. For one exemplary system, a simulation based on Virtual Commissioning was modelled with RF::Suite and WinMOD and extended with a MES test system. The model represents the system behaviour quite well and scenarios can be tested. The test system is reliable and suitable for the simulation of the cell's behaviour. Relevant figures and conclusions can be extracted, which allows comparison between different solutions of manufacturing concepts and varying scenarios can be set.

Table 9: Requirement Fulfilment for Simulation Model

Requirement	**Fulfilment**	**Remarks**
Large scale		Depending on tool performance and modelling effort
Realistic system behaviour		Original software can be used
Suitable for the chosen hard- and software		A selection of tools for different systems is available
Intuitive illustration		3D Visualisation
Adjustable scenarios		Model and processes flexible
Accessible signals		Input/ output signals accessible
Acceptable modelling efforts		Depending on model size and settings
Easy usage		Knowledge about Virtual Commissioning, construction and programming needed
Cost efficiency		Depending on model size and settings
Integration in processes and IT landscape		Virtual Commissioning preparation improves engineering process

The defined requirements are all met at least satisfactory for larger manufacturing facilities, modelling effort, usage and cost efficiency. The system behaviour and accessibility of signals, illustration and suitability for control system are met well. None of the requirements is completely missed. The behaviour of the model is quite exactly the one of the represented production plant, because the original source code has been used. 3D construction data illustrate the model intuitively. Various scenarios can be set and signals resulting from automation can be recorded. Integration of this method in the planning process and IT landscape is possible with acceptable effort.

Virtual Commissioning appears as a suitable simulation strategy tor the given purpose. The selected tools RF::Suite and WinMOD fit for the described example system. Other tools like Process Simulate Commissioning or Virtuos are useful as well, but the differences are not deciding for the given simulation task. For this thesis, the described structure is well chosen.

However, a couple of challenges for efficient implementation remained, especially:

1. Modelling effort is high.
2. High performance for the simulation program is needed, especially for large models.
3. Data availability for modelling must be assured.

The effort to extend the model to larger scales is demanding. Depending on the system size that is to be covered, modelling effort and thus costs rise and computational performance is needed for behaviour calculation and rendering. Hardware cost increases as well which larger models.

The performance of the simulation software, data transfer and calculation speed must fit to the simulation. The performance of the simulation tools is depending on software and system size. Additional simulation PC power would increase capacity. Still, the possibilities to improve performance are limited, especially for large-scale production facilities. This would imply further development of the simulation software, which should not be covered by this thesis. The user can improve the engineering and simulation process. Some suggestions for this improvement are summed up in this chapter.

One often mentioned problem for integration of Virtual commissioning is the cost to prepare models and the question if the benefit is in an acceptable relation to the efforts [Wünsch 2008]. With using Virtual Commissioning, faults can be detected before the building site is opened and can be fixed cheaper so that the quality of the software is better [Zäh et al. 2006], but additional work must be done to prepare the model. A model must be installed, additional engineering steps are needed and the pre-acceptance requires more work in earlier project phases. Behaviour model libraries must be updated continuously. Qualification demands are quite high for Virtual Commissioning: PLC, construction, robot programming skills and simulation knowledge must be combined.

Introducing Virtual Commissioning in the planning process includes costs especially for Hard- and Software, licenses; Training and implementing of simulation in the engineering process; Model preparation and integration in IT landscape; Additional project steps for planning departments and machine vendors

Modelling must be prepared as efficiently as possible. This can mean either less effort for model building or more benefits of the model. With a selection of amendments – most of these measures are already available – simulation for large-scale smart production can be designed efficiently. Possibilities to improve the described first proposal for a model with the focus on testing large, smart IT structures are described in the following chapter and may include:

1. Extend usage
2. Reduce system complexity – reduce scale, restrict to basic or repeating figures
3. Standardisation and model libraries
4. Automatic model generation
5. Software-in-the-Loop approaches spare control hardware

Depending on the concrete situation and environment, the above-suggested improvements in model building of Virtual Commissioning can be used to reduce costs and to increase acceptance.

8.1 Extend Usages

To best advantage from Virtual Commissioning, the models should be used repeatedly [Hämmerle and Drath 2014], [Quirós et al. 2016], [Strigl 2009]. Models can be used not only for initial tests before commissioning, but they can assist planning and production teams during the project. If the Virtual Commissioning model is only used for commissioning, the economical liable bares reason for discussion. With higher efforts to set up the test system, the need for additional usage of the virtual model increases. The model must possibly adopt to several use cases. For example, staff training requires intuitive handling and realistic human machine interfaces. For numerical optimisation of system parameter, usability is less relevant, but the system must be realistic and close to the actual production system.

Training courses with newly introduced products, production network participants (machines, devices or services) are helpful to test and establish machinery. Early Training can be done with the virtualised machines as well. It prepares operation staff for the production lines in early phases. The operator is then better prepared when the line is ready for operation. Additionally, tests can proceed further to the limits of the system without risks of damages causing expensive repairs and standstill or corrupting data [Schumann et al. 2011]. Useful change requests can be fed back independent from production.

When equipment must be changed and new control hardware like NCU or PCU has to be implemented that is not yet used, it can first be coupled with a virtual model. This can hardly be a complete system test and hardware problems can occur with the real components none the less, but a first test is possible and every early found fault reduces breakdown times.

Simulation allows fault analysis and improvement independent from the productive system. Real and targeted system can be compared. Deviation from the targeted system can be evaluated to find malfunction or inappropriate planning. Discussions can be transferred to the office or meeting room, where work conditions are more pleasant and safer. The overview of a complex production system can be improved with a 3D model, because all views can be reached. Programmer can test system amendments first with the model.

With a kind of serious gaming approach, human operators and machines can improve the system playfully. Serious games are regularly used in medicine, science, arts or military, when beyond entertainment serious goals like education or rising awareness are involved [Alonso-Fernandez et al. 2017]. The session can be set up as a digital game, with which the user has to optimise the defined performance indicator. The user can bring in his expertise and intuition, whereas the machine has a powerful calculation capacity.

Simulation models can be set up aligned to the planning workflow. Evaluation starts with first project sketches over to purchase, realisation planning, commissioning and production. A simulation model allows testing scenarios early in the planning process. Each project step can add further information to the model to enrich the available data set of the machinery. This improves the model and aligns it as close to reality as possible. Thus, model building can follow the related project phases. Performance figures can be defined and checked dynamically during the proceeding planning process. With an early simulation model, target figures are updated with every planning phase and the project team can get a feedback system on planning progress. This is most important for newly developed or re-arranged systems.

A simulation model can accompany the real production line throughout its lifecycle:

1. Pre-tests for new functions, software development and improved functionality
2. Staff training
3. Production-parallel fault analysis, simulation of faults, mal-operation or misuse
4. Hardware evaluation for new equipment
5. System optimisation (e.g. sequencing, line balancing, technical availability)
6. Improve software structures
7. Compare planned with actual system state as build
8. Serious Games: transfer human experience and creativity to the technical system
9. Analysis of faults and malfunctions
10. Evaluation and further development of production concepts

8.2 Reduce System Complexity

The effort for modelling should be reduced to an acceptable level. A number of improvements can be included. In cost calculation, complexity reduction can be done by [Friedl et al. 2010]:

- Aggregation, combine similar positions to a complex one
- Average building
- Disregard insecurity
- Disregard current market value of investment

The discussed model of an engine machining line can be reduced so that only one machine in each cell uses real control soft- and hardware. All other machines in a cell can be replaced by simulation, for example by behaviour models. From several repetitive manufacturing features, only one is used.

Another possibility is the reduction of the model to basic part systems with the most impact. Only the important content is considered in depth and less important details are shortened. In general, Virtual Commissioning simulates the whole structure with complete system. Much of the software can be spared to compare concepts. However, omission requires balancing between accuracy of a simulation task and modelling effort. All not simulated components might lead to wrong conclusions. With careful pondering about which content can be skipped, the modelling effort can be reduced to a minimum.

This could at least reduce the choice of possible solutions. The best solutions can be followed more detailed. The described model was set up with a basic Virtual Commissioning model, MES system, but no ERP system. All relevant information was still available.

The model can be enhanced either bottom up (start with components and assemble them to bigger systems) or top down (examine the whole system and work out continuously more details). The model could start on small size and when an optimum for this part is found, it is extended sequentially. Else, it could start with discrete event simulation, continue with a Virtual Commissioning model and simulate details separately, for example, with NC simulation program [Baudisch 2003] or physics simulation [Lacour 2012].

8.3 Standardisation

Successful digitalisation can be supported by standardisation [Bauer et al. 2014], [Pichler 2017]. Standards for data exchange, on behaviour model libraries or on smart components improve efficient modelling. For this, the views of different faculties and disciplines must be conflated [acatec 2013].

Standard interfaces enable easy use of production devices such as sensors, actors, robots etc. as a plug and produce solution [Weyer and Gorecky 2015]. This can be compared with common standard interfaces. All components equipped with an USB interface can be plugged to any PC, driver can install automatically and the device can be used immediately. The standard is accepted, so that the user does not need prepare anything to apply it. Standardised production architectures and reference models enable easy exchange of components and interconnection between network participants. Devices once connected to the production network, install necessary drivers and are immediately set up for their tasks. Similar to this, standardised and easy to use model elements can be established. Once a model element library is prepared, following projects can be set up way cheaper.

The quality of simulation is highly relying on the quality of input data. Construction data and functional description must be available on time and in the required quality and data format. Information might be updated or adjusted during the project. However, preparing a suitable set of data early before commissioning will improve the process [Mewes 2005]. Construction data for 3D visualisation can be exported from CAD or library elements can be prepared [Kiefer and Bergert 2009]. Repeatedly used components can be prepared in a library and reused. CAD data give a view on the actual mechanics. Standardised components and naming allow engineering assistance to create models automatically. Vendors might use different CAD construction programs or use it in different data format and settings. For Virtual Commissioning, 3D CAD data in a data format that allows distinguishing between separate kinematical components are needed. This can be formats like STEP, VRML [Bergert et al. 2010], AML or behaviour elements.

For small companies, it is often demanding to support different data structures or construction requirements. For adjustments on existing systems, it is even harder to receive construction data in an acceptable quality. The engineering processes must be agreed early in the project.

Digital Factory organises necessary construction and process data in a comprehensive database. Data is fed in from different sources and information is made available for various participating departments. Recently discussed is digital twin or digital shadow as comprehensive database for smart factories. A digital shadow is a digital copy of the processes, information and data of a productive company [Schuh et al. 2016]. Production data are recorded. They allow estimating future situations.

Not only construction data must be standardised. PLC Programming standards are common in automotive industry [Kropik 2009]. Generic software pieces can be assembled just like a toolbox to a complete IT structure. This offers a standardised module system, which can be extended and reused independently. Standard reference architecture enables easy implementation of cyber-physical systems and system build-up based on generic components. With these toolboxes, system development can be quicker and less risky. These standards must deal with two opposed targets. On the one hand, it must fit to all possible customer requirements.

8.4 Automatic Model Generation

Simulation models are programmed in correlation to machine software code. Assistance engineering tools are common for repeating tasks in model building. As a number of settings are similar to the PLC code, the virtual model could be generated automatically, related to the planned software structures. Therefore, tasks could be done automatically with engineering assistance tools. The content from the PLC program could be translated to the code of a behaviour model. The more the simulation correlates with the automation program, the better are the results for evaluation. Generic simulation models allow automatic model generation. Some methods have been tested to compile specification to program or simulation code as described in the research project AutoVIBN [AutoVIBN 2010], [Lindworsky 2011], [Neugebauer and Schob 2011]. However, the engineering tool must fit to the actual automation standard.

8.5 Software-in-the-Loop

Virtual Commissioning approaches can be distinguished between Hardware-in-the-Loop (HiL) simulation, Software-in-the-Loop (SiL) and a hybrid commissioning approach. Hardware-in-the-Loop approaches use the control hardware (NCU, PCU) as is implemented in the real machine. Software-in-the-Loop emulates components that are replaced by software tools. Hybrid commissioning combines both approaches by adding real hardware to a Software-in-the-Loop system.

Hardware-in-the-Loop uses the components of the control system, which will be implemented in the machine later. With the real automation hardware, the simulation model is closer to the reality and the interface to the human operator is more intuitive, because buttons, display LEDs and other indication devices can be operated. The components can be implemented in the productive line after commissioning.

Software-in-the-Loop solutions spare the control hardware. They can thus be established before the electrical design is finished and the relevant control hardware is agreed. Standard software code and general process sequences can be virtually evaluated. When the hardware is standardised, the simulation can be reduced to software development. Expenses for modelling can therefore be reduced by the hardware costs. However, using real hardware and interfaces creates a test environment that appears more natural. Training scenarios become livelier when real touch button panels are used. To test interaction with the operator, real hardware is sensible.

8.6 Continuous Improvement

An alternative for simulation is to deduce change requirements with an existing system or further develop an existing standard or reference model. Starting with a given standard, additional components and services can be tested and the best path should be followed further. Thus, rather evolutionary improvement is possible with continuous development. The software can be adjusted systematically, as far as hardware and mechanics allows it. For an established system, adjustments and customisation can be tested, because updates are getting more common with regular software amendments. Hardware often lives longer than software. Thus, a production line requires updates more regularly as software lifecycles are getting shorter.

There are different possibilities to improve an existing system: Prepare a copy of the productive line and use hardware and software separate from the line's equipment, use the hardware from the actual production line and connect it to a test IT system or use the complete productive system. A complete test line is expensive and would be better affordable for manufacturing structures, which are used repeatedly or for major changes that bare high risks in production networks when they are not tested sufficiently. However, using productive line parts requires time slots in which the line cannot produce. During commissioning or production breaks, this solution is recommendable. To avoid any breakage, destruction or interruption on production, a separate model would reduce risks and improve the availability of the productive system. Separate IT structures safe production data from corruption. At any time during operation, optimisation projects can be launched. Observations of the systems show problems and opportunities for improvement.

Target agreement could be established earlier if existing systems are examined in depth and in correlation with future demands of production schedules. The situations on the shop floor can be locked by saving the states of the facility and replay every situation on the test rack repeatedly. To enable fault analysis, the input/output signal setting and all functions and data blocks could be saved and copied to the test system. Thus, the situation can be brought to simulation to check it afterwards in detail.

Development can be done parallel to a running production or parallel to a research or purchase project. With a simulation model, new automation systems can be tested and integrated in advance. This setting would allow a kind of an assessment centre for new IT structures, which enables qualified purchase decision.

9. Validation

The simulation model as described in previous chapters was set up for one exemplary part of the production line. A fully effective model would contain at least 31 PCUs and NCUs and accordingly licenses, simulation performance etc. with all relevant special purpose machines that includes especially:

- Beginning of the line, loading station with order management
- Unload station with flash back signal to ERP system
- Special purpose machines
- Inspection management
- Rework stations

Within this thesis, it was not possible to simulate a complete production line due to time and cost restrictions. A reduced version would bare the risk that wrong conclusions could be extracted from the given information, which would undermine the project objectives. The system must be valid to provide the same information as a real line would give. Instead of modelling a complete line, an existing commissioning project was evaluated correspondingly and related to a simulation model. For a valid proof, the same dataset must be tested, as a simulation model would have produced. In order to clarify concrete evaluation methods, a discussion on an exemplary production system will describe, how the previously discussed targets can be examined. Thus, real-life data give a concrete impression about how explicit results on production data can be evaluated. One advantage for this method is that practical usability of the evaluation method can be proved.

The considered production line is the same as the modelled one in chapter 7 “Simulation Model Setup”. A crankcase machining line has been observed during ramp-up. One month of production data has been extracted. During this time, the line was productive, but had not finished commissioning yet. Technical availability and output had to be raised and faults had to be fixed.

A set of machines are arranged to cells or operations (AFO) that accommodate similar processes. Cells are called with prefix AFO and a number: AFOxxx. Most AFOs have two identical cells for machining processes for redundancy reasons (AFO100, AFO120, AFO140, AFO160, AFO180, and AFO200). Some special machines like assembly cells, loading and unloading station are only single cells.

The workflow follows a sequence of process steps. After raw part loading, several steps of pre-machining and finish machining follow. Attaching parts are mounted in assembly cells. Certain surfaces must be machined precisely in honing machines. Inspection parts and parts for assembly cells and finished parts must be washed first. At the end of the line, finished parts are unloaded and offered to engine assembly.

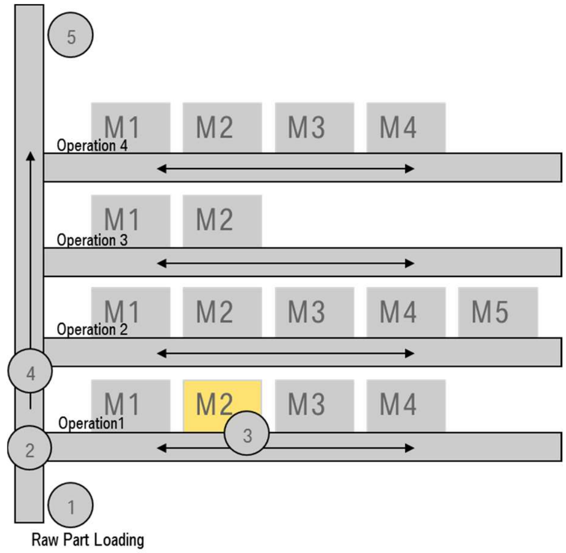


Figure 18: Workflow Flexible Production Line

In order to prove the evaluation method, performance criteria as described in chapter 6 "*Performance Indicators for Digitalisation*" have been chosen. As discussed previously, one of the most important objectives in rapidly changing markets is quick reaction on changing environment and market conditions. Many companies expect smart factories to bind investment first in order to be able to align with the market on the long run; therefore, cost efficiency is less important in this context. Nonetheless, digitalisation must be affordable and investment must somehow pay off, but improved data processing concentrates on further benefits.

Flexibility and transformability is chosen for the practical example of an evaluation method. Manufacturing lines must be able to produce accurately, independent from the workload. The optimum is achieved with zero marginal costs, which leads to complete volume flexibility. Secondly, different product types must be manufactured in arbitrary and variable sequence. The target is to produce in sequence of ordering as defined by the customers' demand. Production should be able to pick up any customer request independent from batch building or scheduling. This leads to complete type mix flexibility. Thus, manufacturing can react quickly on new products and changing markets. In the exemplary use case, flexibility related to changing part type, product sequence and production volume will be examined.

Production performance figures describe the capability of a manufacturing system. The system should be quick in response to changing environment and must be prepared to act flexibly. The targeted performance indicators are correlated to changing system parameters.

Technical availability (TA) defines the share of time in which a machine or line is productive [Kropik 2009], [Takeda 2013]. It is calculated as the ratio of unfaulty operation time to total operation time:

Equation 9: Technical Availability

$$TA = \frac{total\ time - technical\ fault}{total\ time}$$

Net overall efficiency or net OEE describes the ratio of productive time on the whole operation time.

Equation 10: Net OEE

$$net\ OEE = \frac{cycle\ time * ok\ parts}{operation\ time}$$

For best productivity, equipment utilisation (EU) and overall equipment effectiveness (OEE) together must support continuous and efficient production for the available manufacturing facilities [Hartmann 2013]. Not only the machine availability itself is necessary for a good line performance, but also support and transport equipment must be available. In the evaluated machine settings, blockages of transport system effects the operative time as technical fault time, which reduces the achievable output for the regarded cell. Furthermore, different cells condition one another. Technical availability is chosen as relevant objective. The performance of the test system can be judged by the availability of the production facilities. Good results can be seen in high availability.

The task is to enable flexibility of production volume and derivative changes at least with acceptable costs. These must be seen in relation to the benefits of additional flexibility, which includes how much customers are willing to pay for additional flexibility. That could mean that a company, that offers additional derivatives can sell more products or that new offers can be sold for higher costs.

For the described example, it is considered that flexibility is indeed a necessity to keep up with the market's requirements, but the customer is not willing to pay more for the product. This is quite a common situation. The result is therefore best, when there is no difference in the defined target values throughout the whole domain of definition. Marginal costs should be zero in the complete domain.

Production data for each cell have been recorded related to:

- Production volume (numbers of produced parts)
- Numbers of derivative changes in the sequence
- Technical availability

for each shift during the evaluated time range and repeated for each cell.

The technical availability of different cells throughout the observed time range is been put in relation to the number of produced parts and the numbers of derivative changes. This gives an impression on how well the system responds to changing amount and part type changes. Availability should be high for all machines and all cells. When only one cell is inefficient, previous and consecutive operations will be blocked at this cell. Problems with part supply for a cell is included in technical availability, which makes sense for this setting of machinery.

AFO100, AFO140 and AFO180 are cells with rather short cycle times and numerous parallel machines. Resources are plenty. The performance is stable and mostly independent from the production volume. Some of these cells might even be a little better equipped than is necessary or sequencing is balanced better.

At higher volume, fewer results can be found, but the results have higher availability. The highest volume is only accessible with best availability. At lower production volume, the band of technical availability is equally distributed. At lower production volume, the technical availability can be rather poor, because this cell has to wait for previous or following cells in the line. Machines in these cells could operate even more parts, but they are restricted by the line's velocity, especially of the slower cells.

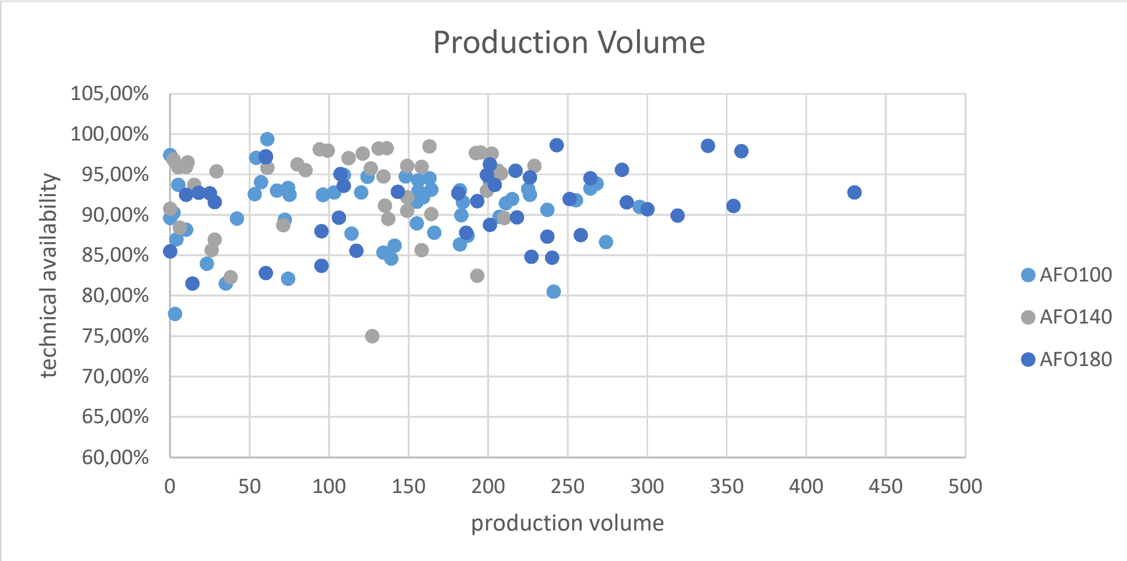


Figure 19: Cells with Constant Technical Availability

Different curve progression can be seen for example for AFO120 and AFO200. These cells also contain machining centres, but with fewer numbers and less capacity. The performance is high for moderate production volume and varies only in a tight belt, but drops for higher volume. The performance is very high only at low production volume. With increasing production volume, the performance drops.

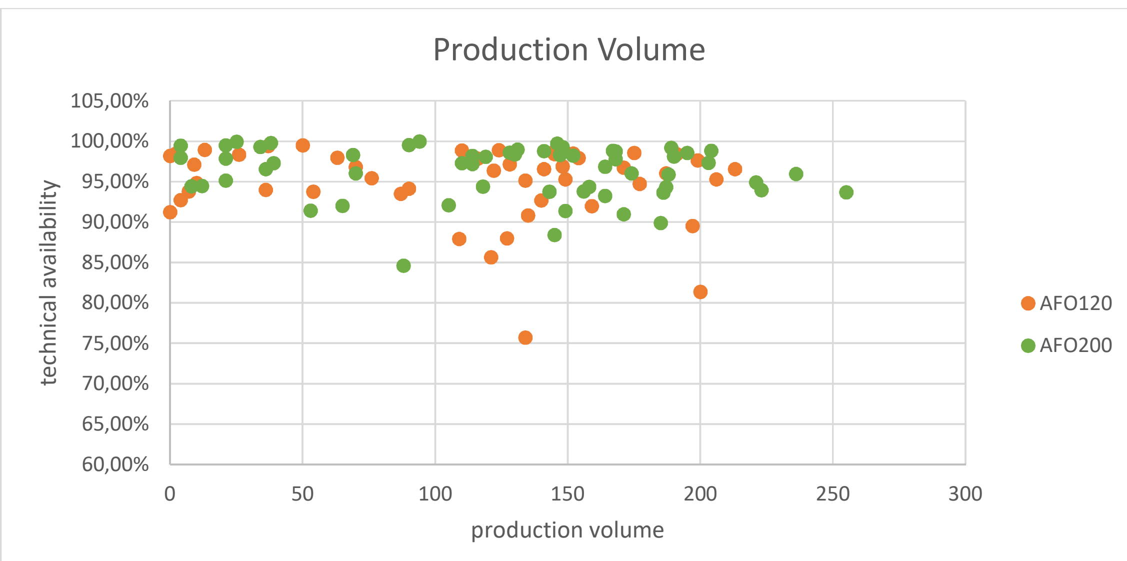


Figure 20: Production Volume

Both figures increase technical availability at the highest production volume, otherwise these volumes could not be reached. For a well-established production line after successful commissioning, the technical availability should settle well above 80% for all cells.

Two different types of curves can be distinguished throughout the line: type 1 is a bright band that narrows with higher production volume, type 2 is bend, starting with high availability at low production volume, declined availability at medium volume and again higher availability for the highest production volume. Highest numbers in production volume are only achievable with high technical availability.

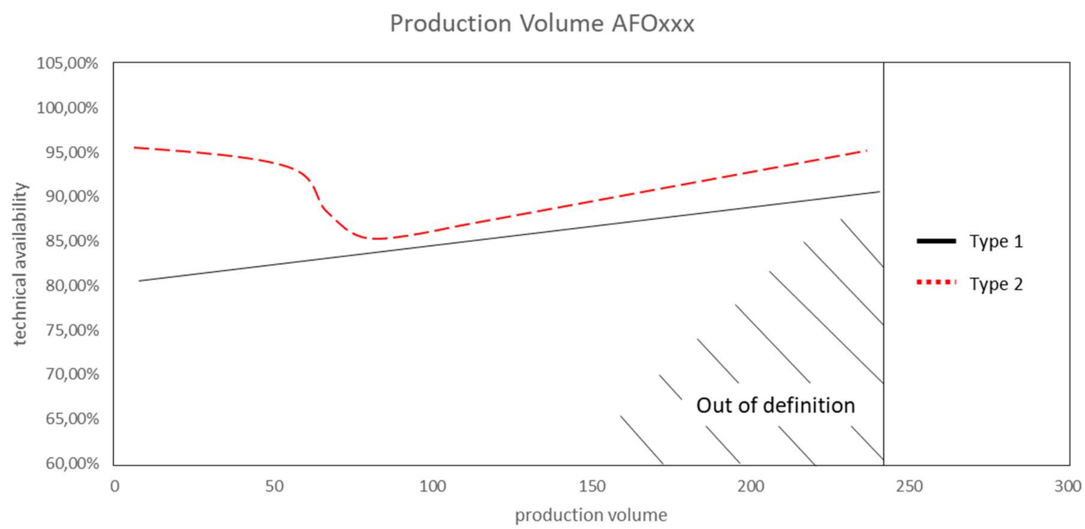


Figure 21: Curve Forms for Different Cell Equipment (Schematic, Qualitative Illustration)

The cells that show no or only little impact regarding production volume are also independent from the frequency of derivative changes. The other less well-equipped machining cells show similar dependency on derivative changes as on production volume.

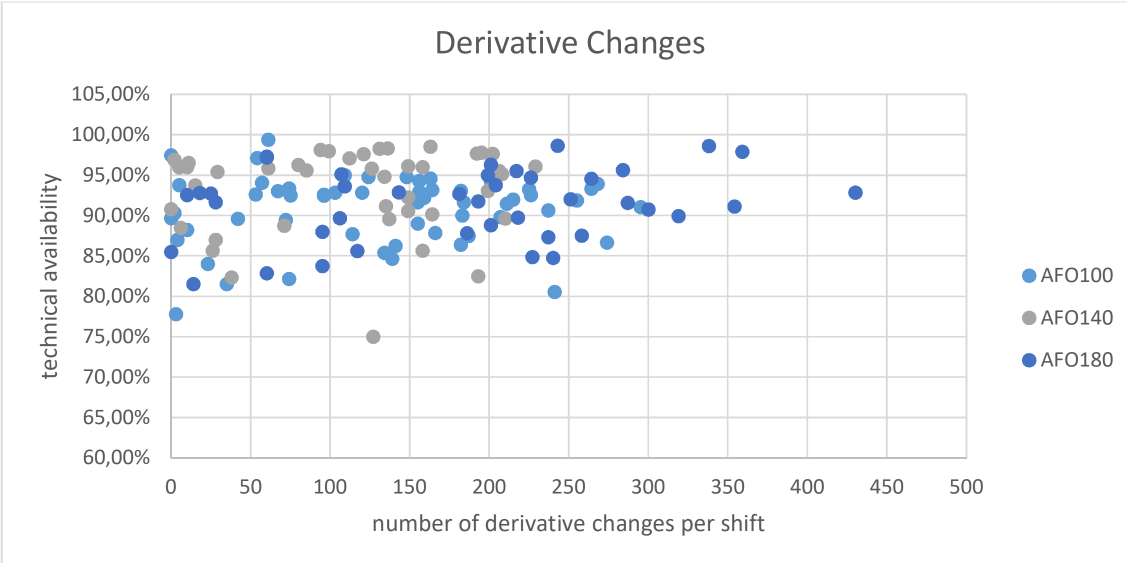


Figure 22: Derivative Changes

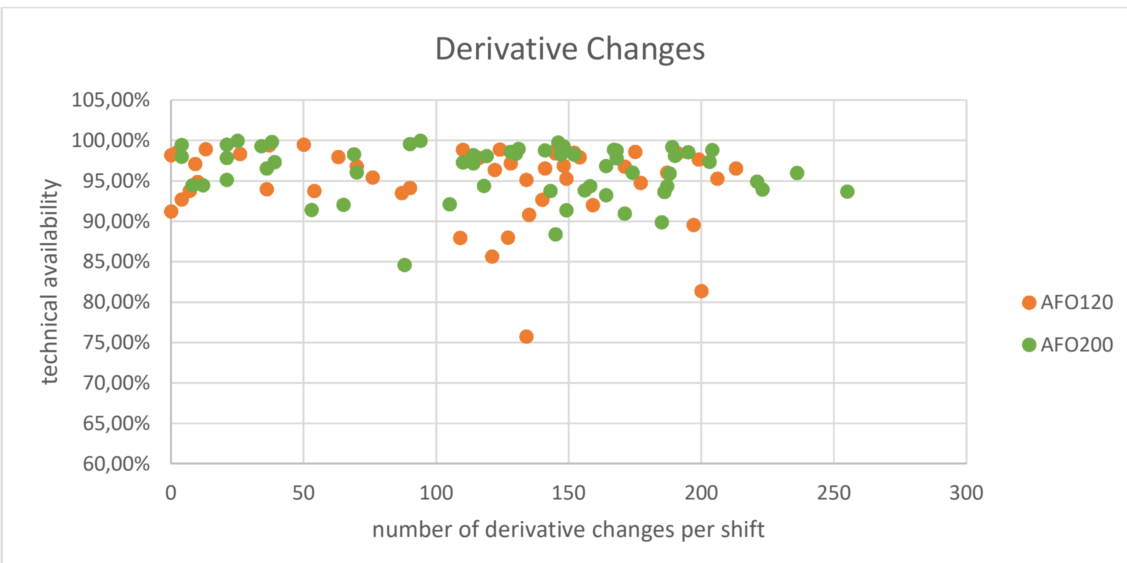


Figure 23: Derivative Changes

The described progression of the curve can be found repeatedly with other cells as well. The peak value might be at different production values or numbers of derivative changes. Two different types of curve progression can be distinguished for both production volume and changes of part types in correlations with technical availability:

1. Cells have a wide band of technical availability, just slightly increasing with highest production volume
2. Cells showing high technical availability for low production volume, which declines for higher figures to increase again for highest volume

These shapes can be found throughout the line for different machines and scenarios, independent from mechanical or organisational problems. It seem immanent for the considered system.

Commissioning showed that the two types of cells correlate with two different groups of performance. The cells in the first diagram (type 1) correlate with those cells that perform better and needed only little adjustment. The AFOs in the other diagram showed more faults during commissioning. The figures and graphs unveil, which cells must be further optimised to increase the overall line`s performance. The diagrams indicate bottleneck cells of the line. It offers a possibility to find cells that are designed with too little and those with surplus planned production capacity. Thus, the planning team can find in advance how sequencing can be steered best.

In this example, the correlation between different cells can only be compared in relation to the complete system: better performing cells show lower technical availability at low production volume because it is limited by other cells. A valid simulation method must be capable of modelling the corresponding system appropriately. For Virtual Commissioning, influences of the mechanics should not be considered. Therefore, time slots with stoppages and breakdowns due to mechanical or organisational faults are excluded from the evaluated data set. A simulation model would have produced similar data, which is checked by a comparison between a Virtual Commissioning model and its actual production system.

The simulation model as described would be suitable to support selecting the most appropriate Smart Factory approach. Problems as described in the introduction would be found during the system development. The targeted figures can be established. Only two particular correlations are tested. Other targets can be evaluated accordingly. Suggestions for discussions are described in chapter 6 “*Performance Indicators for Digitalisation*”.

10. Concept

The chosen simulation and evaluation method is designed for rating and comparing Smart Factory approaches. A couple of suggestions for improving the described structure have been proposed, but in general, the system is usable. This model can be improved further to increase suitability. Suggestions have been described. This chapter proposes extensions of the system's ability for intuitive and smart evaluation.

10.1 Assistance System

Deserted factories are no longer in the focus for digitalisation. Indeed, the necessity of human operator is often mentioned and numerous papers concentrated on labour in the digital world. Picasso said that computer are useless, they can only give answers [Picasso 1969]. This might stay valid until machines gain full autonomy. Until then, it is the operator's duty to ask the right questions.

To reduce the risk on production stability, which can come up during the implementation phase of autonomously operating production lines, the development of autonomous systems can be divided into intermediate stages. First, operation staff is provided with additional information, parts of the processes are done automatically, but the operator still keeps in control of the system. This can be an assistance system with intelligent algorithms as suggested by innovative visions, but with human observation and the possibility of intervention, similar to assistance systems in a car. An algorithm would give suggestions for optimal production strategies. The operation staff can accept it or decline, when they conclude that the suggestion is not beneficial. With a feedback from the human operator to the computer, a learning process can be implemented within this system. When the algorithms are well trained, the computer can take over more control. Key figures are displayed to the operator so that he can still react if necessary. In the end, the autonomous algorithm is better prepared for safe integration.

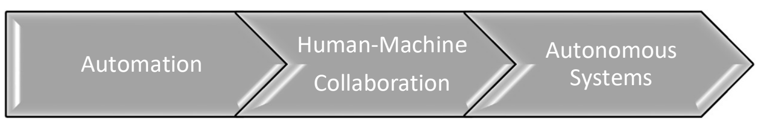


Figure 24: Evolution of Smart Engineering Solutions

It shows that human-machine cooperation is best, when both combine their best abilities. A well-established team of both machines and humans operates the systems more effectively and transparently. Technological knowledge, experience and finesse cannot yet be replaced by machine intelligence, especially in conservative industries. Production staff is needed to turn results from machine learning, pattern recognition and big data analytics into usable instructions, programs and inventions. Neuronal nets must be structured appropriately to perform best, learning algorithms need training settings and pattern recognition or searches are relying on defined paths to reduce search effort. This still requires human operators to adjust the system for innovative new ideas.

Smart algorithms like artificial intelligence, big data analytics and business intelligence cannot be reviewed like common event discrete structures. These systems operate to a certain extend autonomously, instructed by training patterns. They bare an internal logic, which cannot be judged that easy by human operator. To use artificial intelligence in production software, it must be ensured that the algorithm is reliable and can only influence those processes that are safe to interact with. Operation staff must stay informed about the system's actions. It is important that the algorithm can only influence safe processes. Calculation results of an intelligent machine must be transparent. The integration process is crucial.

Overview of the system will be required especially in the beginning when autonomous systems are not yet fully developed, when not all faults are eliminated and the operator is not yet confident about performance and reliability. When an autonomously operating system assigns the processes of the shopfloor, the operator must be able to understand the recent situation of the production line. He or she must be able to alter functions and settings whenever it is necessary. Not only malfunctions must be adjustable. When quick changes or adjustments are needed on short notice, orders have to be changed or testing is needed, it must be possible to intervene rapidly.

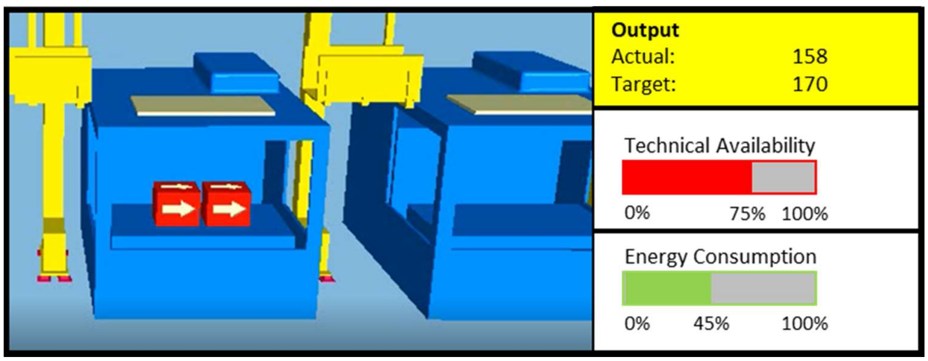


Figure 25: Suggestion for an Intuitive User Interface

Displayed key figures, colour changes and bars show the system's performance. When one overall value can be calculated from all relevant figures, based on weighed figures, limits and constrains between different figures, one concrete value can be observed and optimised. The complete setting of values identify how this result was built in relation to the sub-targets.

Three types of participants or participating groups could join the development process:

a) Moderator
The moderator knows Virtual Commissioning and control software as well as possibilities of smart structures. He guides the team through the development process.

b) Expert
The expert is someone with understanding and experience about the processes to identify new parameter settings and to interpret the system behaviour.

c) Innovator
A colleague with less knowledge or experience about the common manufacturing processes is more likely to question details about the system. Thus, he opens additional opportunities to transform it, liberally from its resent state and long living habits.

Furthermore, the computer can collaborate by finding suitable constrains and learn actions related to the achievements in the given objectives for the production system. The described system can be split into agents with individually agreed targets. These targets must be optimised by each agent and in total. The optimisation can be conducted by either the operation staff, a machine or both in a team. The machine might be able to calculate a vast range of possibilities in foresight and therefore evaluate situations that are more possible. The human operator is more creative and he or she can improve the learning process with further suggestions, which the machine might not be able to consider. The agreed performance figures change related to different reactions of the agent. Positive changes can be followed further. For test data acquisition, the model must be brought into different situations. Reactions and dependencies of the system are evaluated and the performance is optimised. Therefore, relevant input parameter settings must be altered for sensitivity analysis.

The signals for the production system at a certain point could be saved and copied to the simulation model. A situation on the shopfloor that is worth to be discussed further can thus be frozen. Development can be done later on, independent from time and circumstances of occurrence in production. The discussion can be moved from the shopfloor to the meeting room. In the meantime, production can continue. Different following processes or sequences can be checked and compared. After each session, the original state of the line can be recovered and another scenario can be tested. With this, an assessment centre for new production facilities is possible, with a well-established standard even before purchasing. Negotiation between planning department, operation staff, purchase department and vendors can be supported with virtualisation.

With a simulation model arranged in representative size, comparison with the related production line could be used to predict the best next reaction for this particular system. A test system needs evaluation parameters in order to rate operation targets. Thus, deviation from agreed targets get obvious and the production team can intervene beforehand. The system may then establish within the given limits of parameter settings the optimal solution for a given set of input data. The operator must keep the overview on how the systems react and can intervene if necessary. Intuitive indication of production figures enables the operation staff to evaluate amendments on a system and detect corruptive settings. If knowledge and overview on the machine states is provided, better actions and better accuracy can be achieved. Production targets can be established and optimised with a virtual parallel system. This evaluation could include machine learning, big data analytics or agents that negotiate the next actions. In advanced approaches, an algorithm might know from previous situations, how to react in particular situations. The operator can also suggest a different decision or adjust the weight of the performance figures. The new values should be the most beneficial related to other possible next steps.

The amount of test scenarios increases. When the number is too big to be checked completely, a selection must be chosen. Rare situations, which occur only under special conditions, can hardly be found in a structured performance test. Approaches for this are common in big data analytic solutions and pattern recognition. Systematic testing schemes can be implemented in simulation. The simulation and assistance system could propose situations for test scenarios that are likely to cause problems in productive use regarding the defined figures to be optimised. These data can be provided by optimisation, artificial intelligence or big data analytics. The project team must then define constructive measures for the unveiled problems.

Independent from the concrete simulation and calculation setting that leads to optimised structures, even the work on the objects of digital systems and their set-up helps to strengthen the understanding of Industry 4.0 content.

10.2 Mathematic Model

Data is nowadays widely available and easy to acquire. However, data themselves are useless, real value can only be raised in the information, knowledge and experience behind it. Data processing and evaluation is an important part of digitalisation [Ehrmann 2014], [Radetzki 2018], [Trefler 2015].

The previous chapter described the evaluation of an exemplary production system. Depending on the gradient of either production volume or number of derivative changes in relation to the technical availability, the system's performance can be interpreted. In the described example, the acceptable marginal costs must be seen as zero, because additional flexibility would not allow additional costs. In the meantime, the value for flexibility to change for example from diesel to petrol engine production have increased rapidly. When information is available, about how much additional value a flexible production system can generate, the targeted curve can be align to this cost curve. The acceptable costs can be calculated as described in *Equation 1: Optima Flexibility* [Corsten and Gössinger 2016].

For a cost-benefit-calculation, both advantages in flexibility and costs for the development must be quantified and put into relation. There are numerous possibilities for additional value. For example, an additional amount of products that could be sold, which brings in a gain in profit. New products can be included to an existing line to avoid purchase of an additional production line. Further derivatives would increase sales figures for import-restricted markets. Additional costs for flexibility must be covered by additional income or other benefits. Sustainability or enhanced ergonomic might be among these benefits. For innovation, it is often hard to predict costs and benefits in advance, especially in early states of research. Often it simply improves the process or enables transparency. Either all positions of the cost calculation must be related to cost figures or a bonus malus system must be established, for example as a kind of cyber currency, which relates all production relevant costs and benefits. A number of parameters to be developed can be defined and their deviation evaluated. The targets might condition or exclude each other. For example, when quality is improved, this might reduce cycle time and increase costs. The overall optimum must be estimated or calculated. The indicators can be weighted differently, depending on the purpose. Priorities can be defined for each agreed target, for example 40% for quality, 30% time and 30% cost. Thus, an overall value can be calculated and compared.

The output of a system is evaluated and optimised. The recent state can be described as an output vector including all relevant conditions.

Equation 11: Dynamical Evaluation

$$\overrightarrow{objectives} = \vec{o} = \begin{pmatrix} \overrightarrow{time} \\ \overrightarrow{cost} \\ \overrightarrow{quality} \end{pmatrix}$$

Possible machine states can be evaluated dynamically regarding the recent machine environment and production conditions. To find the best next step, multidimensional trajectories for different states can be compared, related to the given objectives, similar to simulation methods [Borshchev 2013]. Every incremental time interval, the algorithm has to check for all possible next steps, which decision is the best for the given situation. The recent states are calculated by an algorithm. This can be an analytical calculation, artificial intelligence or any other suitable algorithm. The next step changes the constellation of targets. The following constellation will be evaluated starting from recent state plus the expected changes from the next decision.

Equation 12: Dynamical Evaluation

$$\overrightarrow{o_1} = \overrightarrow{o_0} + \frac{\partial \vec{o}}{\partial t} = \overrightarrow{o_0} + \begin{pmatrix} \frac{\partial o}{\partial time} \\ \frac{\partial o}{\partial cost} \\ \frac{\partial o}{\partial qality} \end{pmatrix}$$

The target trajectory would lead to an optimum in all considered figures or an acceptable compromise of diverting targets, possibly within agreed limits. Trajectories that lead toward beneficial states of the system can be followed consecutive and allow continuous improvement. From one point in space and time, the next system's reaction must be seen in advance. Then, a range of possible actions can be compared and the best one is to be chosen. For systems or partial systems that can be described with mathematical formulas, optimisation can be run with operations research, business intelligence or operation management methods. Corresponding to mathematical constrains related to productivity as defined in chapter 6.2.1 *"Productivity"*, objectives can be calculated partially and marginally.

Manufacturing processes are often discrete events. General calculation methods for finite state machines, petri nets or stochastic calculation [Lunze 2016] can be used for PLC or NC based automation systems. Operations research, business intelligence or operation management support the evaluation. Mathematic models are regularly applied to develop abstract optimisation strategies for business and operation systems. The detailed equations are highly dependent on the considered systems, relevant objectives and cost structures and will not be further detailed here. Methods for calculation and modelling of production content are described in chapter 2.5 "*Evaluation of Production Systems*" and can be implemented in the evaluation system as needed. Relevant performance figures for smart factories are described in chapter 6 "*Performance Indicators for Digitalisation*". Productivity or flexibility can be evaluated with every change in the software and thus the best setting can be found. Some figures strive towards an optimum, for example maximum technical availability or minimum energy consumption, others should settle at a saturation point. The targeted state for the selected figures must be defined. Different production states can be compared to find and avoid problematic states.

10.3 Flexible System Architecture

Flexibility and changeability as requested for smart factories demand major refurbishment of recent production structures. In order to enable decoupled production lines, a process sequence must be defined in which the part can skip steps and get back to them when the demanded resource is available again. The process must be split into independent operations of which the machine or the workpiece can define which operation to request next. For this concept, the planning team must be able to define processes that can change sequence. Processes must be independent. Sequence change is only possible when the part can be processed in different orders.

Part transport must be highly individual to all machines or cells. The part must remember where it already has been and where it still needs to go. The process must be transparent and result and quality data must be traceable throughout the whole process. Parallel resources must be loaded independently. Smart transport and logistic systems have to be installed to enable adjustable sequences, resource allocation and resource sharing. All offered facilities must be reachable. High-rack storages can balance infeed and outfeed based on the demand of previous and following line parts or products. Production resources must negotiate the next processes. Therefore, transport systems must receive additional internal intelligence. However, logistics do not add any value to the products, but they hold the ability to implement smart support functions that have to pay off for the additional costs in system setup. Auxiliary processes gain additional value through digitalisation.

Resources must be flexible to process different part types and operations. Flexible-purpose machines, which can provide a range of operations with open usages support easy-to-change manufacturing, are best suitable. Flexible machines that can operate various part types in flexible amount and sequence of derivatives, adjustments must be handled adequately.

The effort to keep multiple-product lines operating stably is more demanding than for single-purpose machines. Amendments of controls and mechanics for every additional product type are needed. New derivatives must be assigned to the machines and new parameters must be introduced. Additional work plans, NC programs and gauge plans must be prepared and processes might need adjustment. Transport system, superior management systems and other participants might need changes as well. Mechanical equipment might need amendment, for example gripper, pick-up positions, sensor and actor (pneumatic cylinder, motors…) positions and size, seating and new tools if necessary. The more combinations are included the more complex the lines will be. A lack of overview about data and process causes data mismatch, errors in shift registers and slower problem solving.

It is advisory for production stability to prepare emergency strategies for unforeseeable situations. Critical machines should be installed in redundancy. When a part can unexpectedly not be processed at an assigned station, it must be removed from the active workflow paths to liberate the process. The system must be safe to be used stably under any possible situation.

11. Conclusion

11.1 Summary

Target for this thesis was to establish

a) a simulation environment and
b) an evaluation method

to test and develop production IT. The focus was to establish smart factories and discuss proposals related to benefits and risks of digitalisation. An example for both a modelling and evaluating method has been described.

The model was built up with as little effort as possible to increase its profitability and acceptance. Common software tools have been used as far as possible. The simulation method is based on Virtual Commissioning, enhanced by additional applications for superior IT systems, test server and database. Relevant production data from ERP are transferred to the MES system. All necessary information about order management, quality control, product data, tooling and gauging are available in the MES system. Therefore, simulation of the ERP system is not needed and has been spared to reduce modelling effort. The Virtual Commissioning model should cover all necessary equipment of the observed system, which is at least one instance of every relevant participant of the chosen production system, in this example at least one machine, transport system, if necessary additional special purpose equipment and the required superior management system, as far as necessary.

The simulation can be further established to assure the user's acceptance and to improve the model building process. Suggestions for further development for efficient and effective model building are summed up in chapter 8 *"Verification"*. These are for example reduction to the most necessary content, standardised systems and processes and additional use cases to enhance benefits. On the other hand, Virtual Commissioning tools improve continuously which supports better simulation.

Second task was to develop a suitable evaluation technique. Benefits of innovations are hard to calculate. Targeted performance figures have been discussed and countable figures are available for comparison and optimisation routines. Digitalisation has additional purposes compared to the previous stage of technical development. Efficiency gain of preceding automation phases continues, but the abundance of data and information serves for additional benefits, for example the ability to adjust to changing market environments or transparency. One exemplary target, flexibility of production volume and derivative changes, has been discussed in depth, based on a real production system. The evaluation method disclosed the performance of the observed system well based on constrains that are valid for the considered figures. With the described method, inappropriately operating cells can be identified and discussed.

Three objectives have been described: the ability to adjust to changing environment, economic contribution and transparent processes. The exemplary simulation and evaluation task dealt with quick reaction on changing environment. Further figures can be developed accordingly. The process of evaluating a system can be adjusted and used for other systems and further purposes than chosen in this thesis. Approaches for fundamental correlations are proposed and can be applied to any given production system. An assistance system has been developed to support smart production development.

11.2 Résumé

Detailed research questions for this thesis were:

1. Does a simulation model allow sufficient testing on smart production IT approaches and how can the model be set up?
    a. Which requirements are relevant for the model?
    b. How can a simulation method for digitalisation approaches be implemented and operated appropriately?
    c. How can evaluation be implemented during the planning process?
    d. To what extend and at what point of the planning process can smart production IT be compared and optimised best? Are there limits for this method?
2. How can smart production systems be evaluated and compared?
    a. What are the major objectives and requirements for future production systems?
    b. How can new production structures be compared and evaluated?
3. Which results can be derived from a simulation and evaluation method for Smart Factory approaches?
    a. Which results can be deduced from smart system evaluation?
    b. Do alternatives for simulation exist?
    c. Can correlations be found for digitalisation strategy?

Answers to the research questions RQ 1a) – RQ 3c) are summed up below.

11.2.1 RQ 1a) Requirements for the Model

Two special requirements are relevant for this thesis:

- The software source code must be simulated in detail
- The model must be large enough to cover large-scale production facilities

Some other general requirements must be met nonetheless, but are not specific for the given purpose:

- Hardware and software requirements for the emulated control system
- Intuitive display of the system
- Scenarios must be adjustable
- Signal of the PLC must be accessible
- Acceptable modelling effort
- Easy usage
- Cost efficiency
- Integration to process and system landscape

A suitable simulation model must describe software logic in detail in order to develop smart IT structures. The autonomy of smart algorithms can only be tested and developed with the real, not abstracted program code. For larger production facilities, discrete event simulation is well established. However, with discrete event simulation, software logic is abstracted and cannot be described in detail and developed further by these rough sketches. Virtual Commissioning describes software logic quite well. This model must span large-scale production facilities. Therefore, the model has been enhanced by additional management systems; in this case, MES is sufficient for the required tests.

Simulation of large-scale production facilities demand high modelling effort and calculation power. A range of suggestions for improved Virtual Commissioning has been published and can be implemented to enhance the model. Some of these proposals have been summed up here and are put into context with the task of this thesis: extend usage, reduce complexity or automatic model generation.

11.2.2 RQ 1b) Implement and Operate Simulation Method for Digitalisation

Available simulation methods have been described and compared. Research projects developed various methods to test manufacturing equipment to support engineering and production planning. Commercial tools and applications are commonly used for various automation tasks in manufacturing from fieldbus level to ERP.

One suitable suggestion for a test system is described in depth. Virtual Commissioning has been chosen as a first starting point and is extended to support testing of smart production approaches adequately. This includes especially the MES system. The ERP system was not essential in the considered case. Simulation therefore stretches from the field level to the MES system. With this model, large and intelligent structures in production IT can be tested appropriately.

With a model prepared as described, development of smart manufacturing structures can be supported. However, modelling effort must be reduced and additional adjustments can improve the simulation. Performance and modelling effort is still demanding for larger facilities. Improvement in modelling and evaluation is required. Amendments of the simulation tools have not been considered. Some possibilities for Virtual Commissioning user have been suggested, described and discussed. Reducing the system size, standardisation and libraries or multiple usages for additional purposes can increase its benefits sufficiently.

11.2.3 RQ 1c) Implement Evaluation to Planning Process

Evaluation methods can be included in a simulation environment for standard planning processes. Virtual Commissioning is regularly used for pre-acceptance of constructed production plants. However, one model can accompany planning projects from early drafts to the operating system. With multiple usage of the model, efficiency can be improved and construction data are completed consecutively. A range of suggested use cases for additional purposes is collected, for example early staff training, intuitive project meetings, where the team can discuss tasks based on a virtualised copy of the line, or an online assistance system to support the operation team during production. The model can accompany the whole planning and commissioning process with enhanced details for each planning step. Model optimisation and implementation in the planning process is continuing.

Graphical display of production targets and dynamic calculation of relevant figures allows developing and establishing new concepts intuitively. A range of possible suggestions for serious gaming is proposed in chapter 9 *"Validation".*

11.2.4 RQ 1d) Possibilities and Limitations

A virtualised model of manufacturing equipment helps to implement digitalisation projects from early testing until optimisation during production. The model can be used for evaluation and development of production content, for example, product and process sequencing or order and resource management. Virtual Commissioning allows development of smart production IT, because the original source code is implemented. Data exchange and workflow could be modelled in detail and new structures of the production IT can be established.

However, a couple of problems occurred during the implementation. Construction data have been not available, not complete or in an inappropriate data format. This demands additional effort for model building, especially for larger facilities. The performance of the simulation software was limited, especially when many control units had to be coupled. The benefits are especially depending on the modelling effort. A number of adjustments of the simulation model have been suggested. Model building can be enhanced for example with complexity reduction, automatic model generation or standardisation and model libraries.

Model building can be improved when system size or details are reduced. The Virtual Commissioning model must be extended to the necessary size. For the described case, a test server and database for the MES system was implemented. The ERP system was not needed. Improvements in simulation software have not been in the focus of this thesis. Software-in-the-Loop solutions can be established with fewer costs, because hardware expenses can be spared. Cost efficiency is higher when the model is used repetitively.

Virtual Commissioning requires a running software code. PLC project and robot programs must be available and running without faults in order to start simulation. An existing production line or a software standard can be developed further. Re-use and re-structuring system standard can be established. However, if a project is chosen to start from the sketch, a complete software must be prepared to get the Virtual Commissioning model running. With a well-established standard or reference model, the setup can be executed with appropriate effort. Construction data acquisition can be improved with systematic and standardised databases. Comprehensive data processing structures have been established for example in the field of Digital Factory, as digital twin or digital shadow.

11.2.5 RQ 2a) Objectives and Requirements for Future Production

Target for optimally operating production systems are various. General targets of costs, time and quality must be met independent of the project background. Digitalisation addresses additional objectives that are related to IT content, big data streams and smart algorithms. It has special requirements and objectives. Technological development is described in depth, especially in terms of digitalisation. Requirements and expectations have been compared to find relevant impacts. Targets are discussed in detail. Smart production approaches do not only offer further increased efficiency, but also additional purposes of interconnected, smart networks. For the suggested evaluation method, targets for smart manufacturing are discussed. Future production systems bare advantages especially related to continuous efficiency, transformability of manufacturing structures and transparent processes. According to these objectives, constrains have been established, which makes evaluation available for smart production IT.

General planning figures must be reached independent from the smartness of the system. Beyond that, these selection on performance figures focuses on three main targets:

- Efficiency and productivity
- Flexibility and changeability
- Transparency in processes

11.2.6 RQ 2b) Compare and Evaluate Production Structures

Calculation methods for production systems are common in cost calculation, supply chain management, business strategies or operations research. Methods from these or other areas can be implemented in the model to establish smart structures. Artificial intelligence, big data analytics or knowledge-based systems can be implemented and rated. Advantages and disadvantages can be compared and discussion about the best suitable system can be done in the meeting room. An intuitive test and assistance system as described can support decision on how the system should be established.

Objectives of digital structures have been evaluated. From these targets, suitable comparison figures are selected for a system evaluation. The evaluation of an exemplary production system showed that its performance could be evaluated with the suggested method sufficiently. This is described in chapter 8 *“Verification*” in detail. This practical example depicts concrete processes to develop digital manufacturing structures. The evaluation method provides a concrete example for system optimisation based on available production figures that are utilised for digitalisation strategies. Flexibility was chosen as a practical example. Evaluation of production volume and numbers of changes in relation to technical availability shows that insufficiently working cells can be found using data analysis. Therefore, early testing has been proven supportive.

11.2.7 RQ 3a) Achievable Results

Main task was to develop a method that allows estimation and development of new production concepts. Though development on smart factories is discussed regularly for years, practical examples on smart series production facilities are still not common. There are always more opportunities than can actually be handled. The best solution should be located among an abundance of possibilities. The exemplary evaluation showed that suitability of a certain process for a certain target can be examined and poorly operating machines or cells can be detected. This shows that the method’s performance is useful for testing, because issues in the system become evident with the technique. It is valid to test and improve smart production IT. The results are depending on the targets of the evaluation.

In this example, only performance in relation to varying production volume and changing product types has been compared. Additional targets can be tested accordingly. As production environment might vary considerably, other companies might need to adopt other parameters, but a general idea about needs for digitalisation in manufacturing can be obtained from the example discussion. An assistance system to develop smart production structures has been established. Common calculation methods can be included in this model.

Concrete targets help to structure the overwhelming issues of future production. One simple but effective advantage of simulation is to consider which performance figure must and will be influenced by the smart solution.

11.2.8 RQ 3b) Alternatives for Simulation

Simulation is possibly one of the most efficient technique to develop smart factories as it reduces resource requirements. It is also a safe method, because it is independent from the real production system. However, the first installation of the model is expensive.

Another opportunity to establish smart manufacturing structures could be to use the existing system during times of no production and improve it further continuously. The risks to violate regular production when a test fails are high and freely available time slots for testing must be kept open.

The described evaluation method can also be used for improvement of a running production line as an assistance system. This enables the continuous development of existing lines. The human operator keeps control over the system, but he gets necessary information to define the best next actions. Therefore, suitable performance indicator for digitalisation must be set and observed.

Calculation models or continuous improvement of an existing system is possible in general. Intuitive evaluation is best with a virtual model. To support the human operator during the development process, simulation is advisable.

11.2.9 RQ 3c) Results and Correlations for Digitalisation

A test method has been established in this thesis. Some general results can be seen from this basic work. One important achievement, deriving from the discussion about digitalisation strategy, is an overview of the main objectives that are relevant for Smart Factory approaches. Digitalisation extends automation to additional purposes. Flexibility is a major driver. Fast product and derivative changes, volatile markets, globalisation tendencies and new products, processes and materials demand regular adjustment to changing environment. Efficiency and productivity is still important, but other targets have come to the focus of digitalisation strategies. With the upcoming abundance of data, transparency is demanded, but it also allows, further knowledge about the manufacturing environment to emerge.

The performance of a manufacturing system has been examined to prove the concept based on concrete production figures. Production volume and number of derivative changes can be limited. The limits of the line can be made obvious. This allows conclusion about necessary adjustments for poorly operating cells.

Further substantial testing on different systems and settings should allow a more systematic view on purposes and problems of digital manufacturing. A range of calculation methods is common for a production environment that can be included in evaluation routines, for example supply chain management or cost calculation. Other techniques are in development, for example artificial intelligence, operations research or big data analytics. Appropriate methods support the simulation model of the plant. Serious gaming combines human and computational intelligence. Assistance systems can be implemented as intermediate step towards fully automated lines.

11.3 Epilogue

Digitalisation tendencies proceed to influence producing industries. Emerging IT capacity is the expected enabler, but also a challenge for future production. The choice of solutions for data acquisition and processing tools in manufacturing environment is huge, which makes it exceedingly difficult to keep an overview of the market and find appropriate solutions for a particular situation. Improved services demand an increasing use of computer evaluation, data storage and algorithms. Thus, complexity is expected to increase for highly flexible machines and production lines.

Digitalisation strategies bare incalculable risks on the spent investment. Costs for newly implemented systems can be huge. Therefore, companies must be able to make well-informed decisions. Risks and consequences of IT integration projects must become clear as early and as concrete as ever possible. Otherwise, the risk is high that changes destabilise processes. Many projects turn out not to meet requirements and customers struggle with complexity. Unforeseeable faults and deviating strategic implementations are the result.

With a comprehensive test environment, new solutions can be coupled and tested before they are introduced to the factory. Necessary objectives for digitalisation strategies must be discussed carefully to find suitable calculation possibilities. Based on the described or other relevant aims, appropriate evaluations and development approaches can be executed. The suggested setting of a simulation and evaluation system is an appropriate method to focus decision on digital transformation in manufacturing on relevant objectives, in this example on quick adjustment on changing markets and environment. Other measures to prepare smart production systems might be appropriate for other sectors or circumstances; discussion on expected targets for this refurbishment is highly advisory.

12. Outlook

Early tests for smart production systems are highly recommended to avoid poorly operating systems and false investment in misleading digitalisation strategies. Simulation enables smart software to spread to the factory environment with acceptable risks. Engineering and production specialists can integrate new solutions based on implemented evaluation routines and defined performance targets. Requirements for manufacturing will rather increase with digital, global and volatile markets. Expecting continuous digitalisation, a lot of testing and trial must be done to adjust the systems accordingly.

The described test example is based on only two selected target figures: production volume and numbers of derivative changes in correlation with technical availability. As most important targets were chosen flexibility and changeability of production volume and derivative mix. System amendments, for example storage capacity, amount of resources and transport systems or targeted output can be implemented and changes of the performance of previously mentioned objectives must be evaluated. Input parameters for the simulation system can change: for example, availability and number of part types and the amount of workpieces in the system, the number of available and deselected machines or the amount of buffer places and logistic storage.

Various questions about the considered system can be examined. The spot of time, when machines, cells, or transport elements are stopped can be tested or how much delay can be caused until maintenance and operation detect and repair a fault with complex systems. How would the system react best on faults or special situations? How much information can one operator observe without being irritated? How much documentation is needed and helpful? Which tasks are best to be combined at one workplace to keep the operator’s attention high, but without leaving operation staff overstrained? Which operations can be combined, what are the limits of complexity and system size? These and other questions help to improve the system’s performance.

Changeability will be enabled by quick system amendment and testing. Other useful targets have been described and can be developed with the suggested method for other systems as well. Related to this, different performance indication figures can be compared. Instead of technical availability, other useful targets to be considered might be output, throughput, energy consumption, mean time to repair etc. More than one figure can be related, for example the dependencies of the technical availability in correlation to both changing production volume and derivative changes. Furthermore, the evaluation can be done not only statically and independent from the point of time, but also considering previous developments.

With extended evaluation, digitalisation provides additional labour both for qualified and support staff and enhances the functionality of production. Automation had the clear goal to reduce human labour and replace workers by machines. Therefore, discussions were common whether robots will cause mass unemployment, when robots adopt human finesse and creativity. When benefits in human-machine cooperation settle, this additional labour should pay off on its own and can provide jobs for computer scientists and experienced production staff. Data analysis demands process experience that by now still requires human skills and thus provides labour. Well-established digital designs could provide additional labour.

There is a significant opportunity that with additional benefits of digital and interconnected production networks a new kind of work can emerge. Different from previous automation strategies with the target to replace human jobs by machines, the value of the human operator and their ability in combination with the machines' competences can raise output and value-added.

All participants in these global production networks need access to a pool of information concerning product, production, methods and organisation. Considerable amounts of data must be processed. Suggestions for suitable models are described and will be established further. Variations of scenarios, observed systems and discussed objectives for smart systems will enhance experience on the most useful approaches. Further research can provide figures, conditions and constrains, which gives useful suggestions for general system design of smart production devices and services. Performance optimisation can be described mathematically and integrated in an assistance system. Virtual Commissioning models support signal display and calculation applications. These tests should allow a deeper understanding of system correlations:

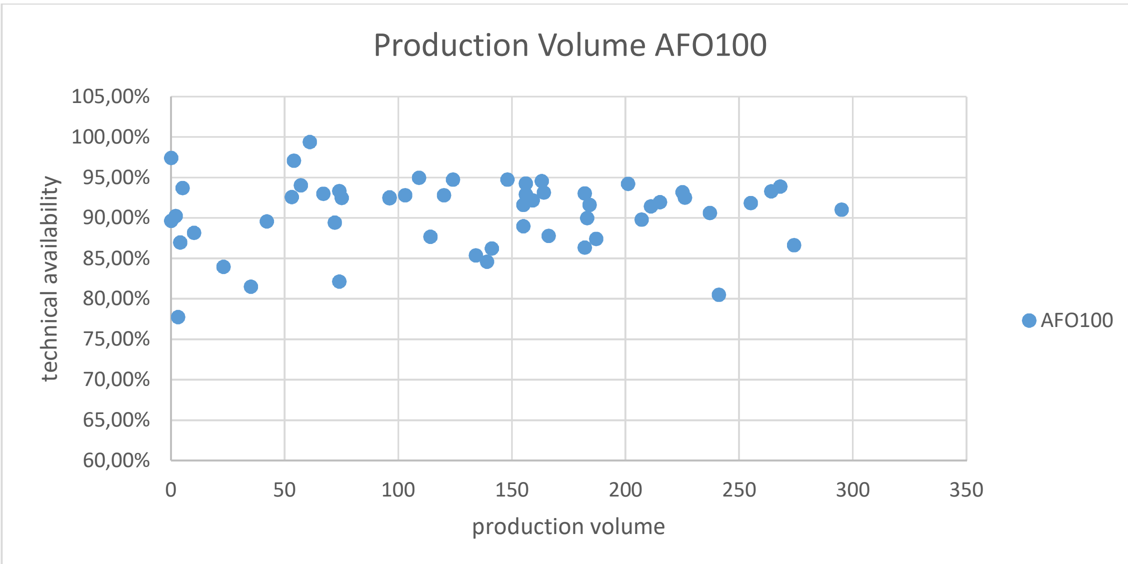
In general, digitalisation must stabilise the important sector of producing industries and enable it to catch up with global development. However, the objectives of chosen solutions must support this turnover. Whether it is more flexibility or transparency, the proposed purpose must pay. The discussion on the matter extends the understanding about digitalisation and helps to focus on the relevant development.

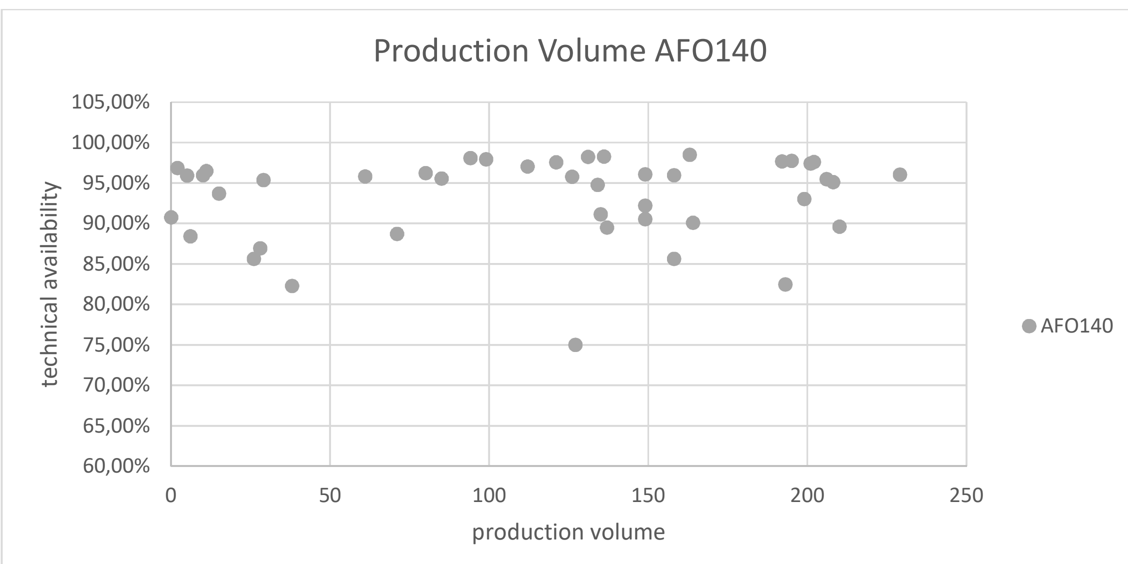
13. Appendix

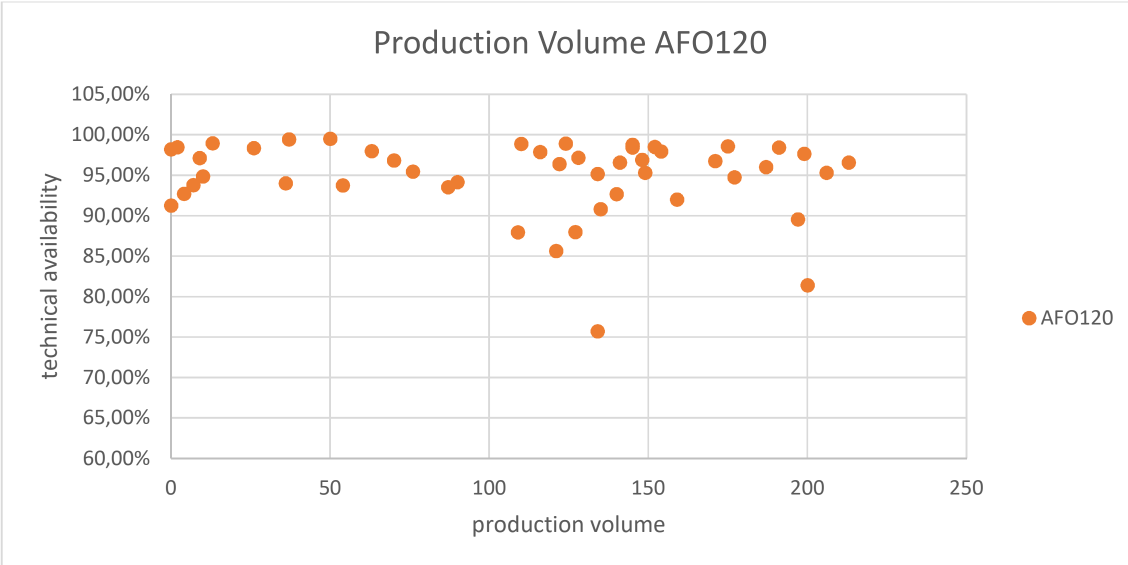
13.1 Results of Test Data Evaluation

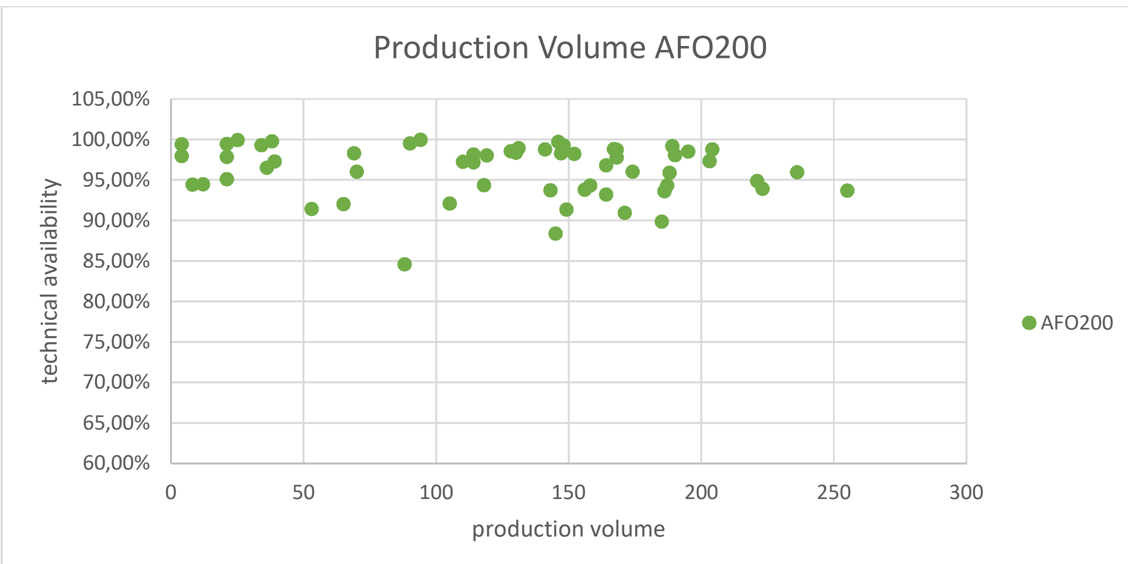
In chapter 9 *"Validation"*, a production system has been evaluated. The results are displayed here in detail.

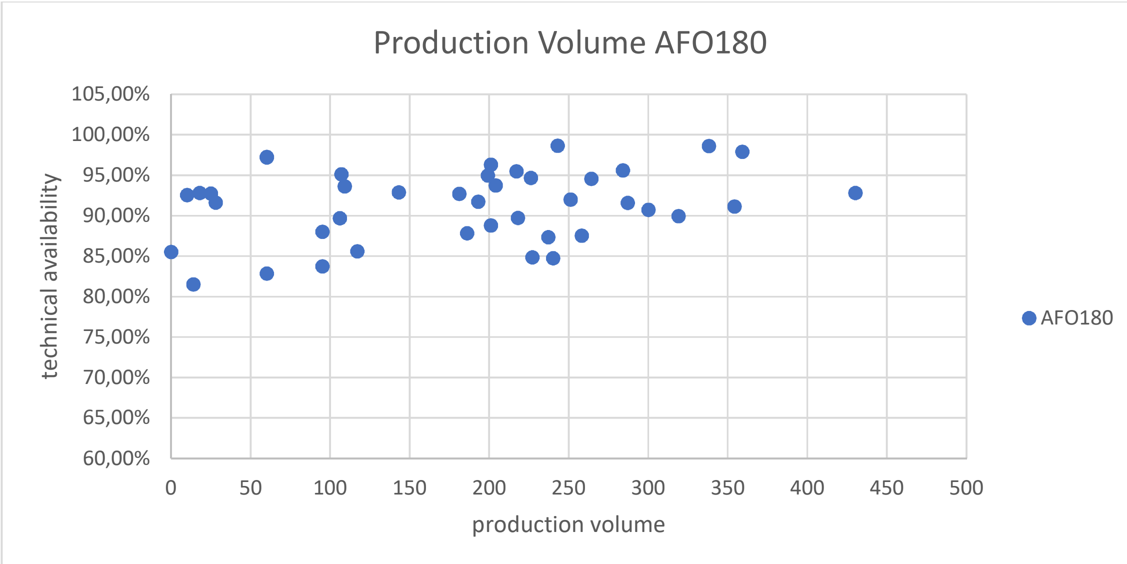
13.1.1 Cell Overview - Production Volume

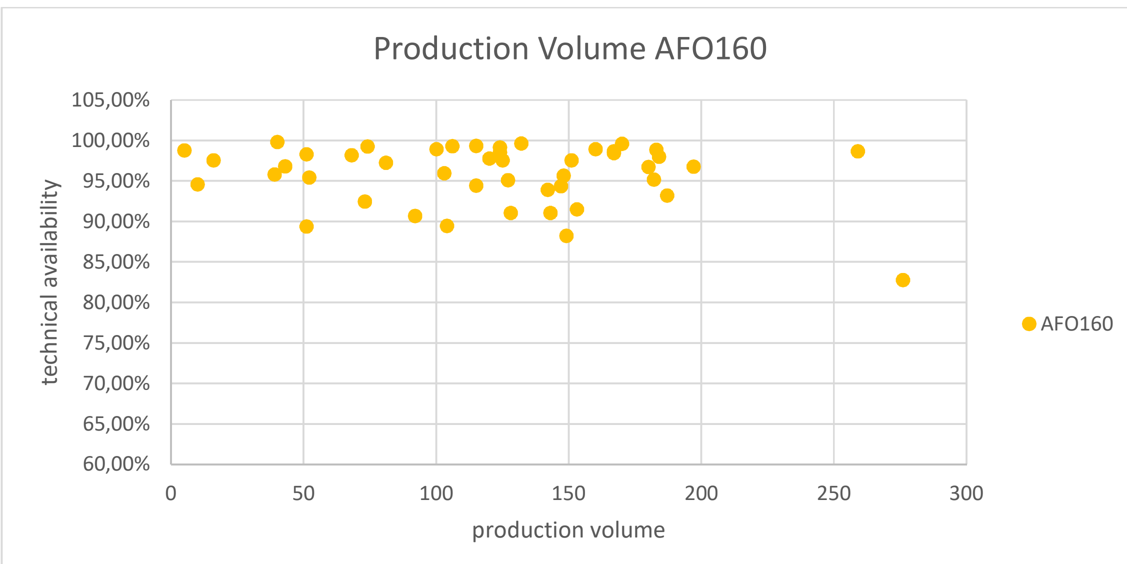




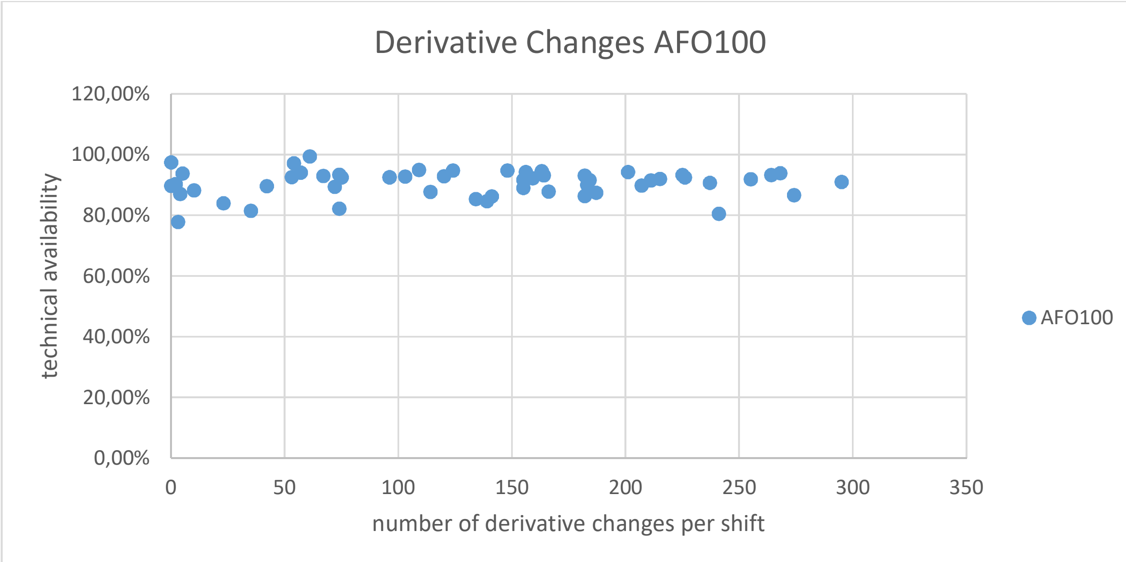

Production Volume AFO120
105,00%
100,00%
95,00%
90,00%
85,00%
80,00%
75,00%
70,00%
65,00%
60,00%
technical availability
0
50
100
150
200
250
production volume
AFO120

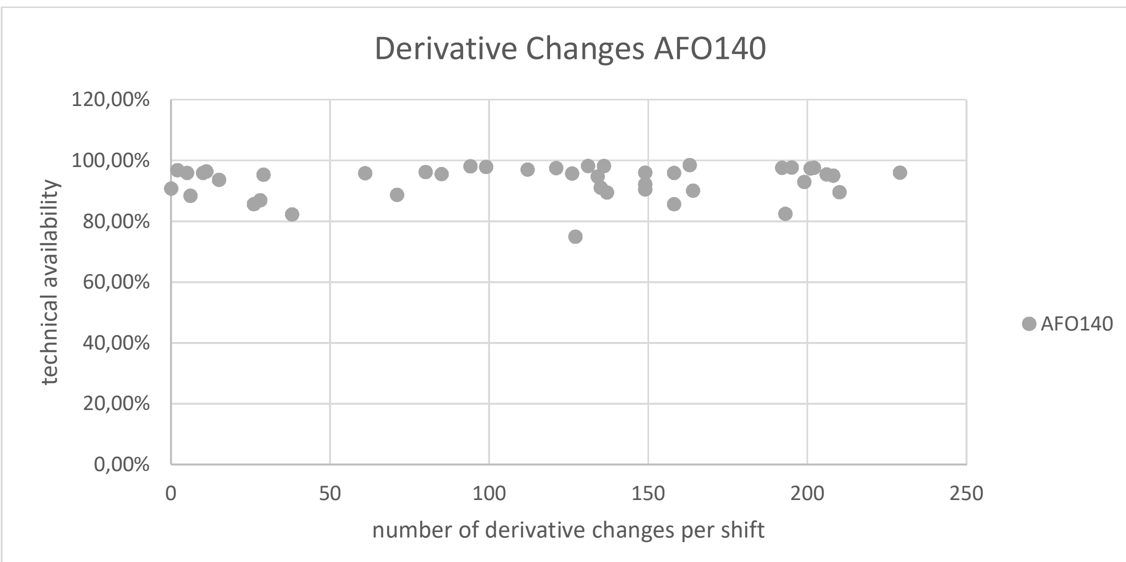

Production Volume AFO200
105,00%
100,00%
95,00%
90,00%
85,00%
80,00%
75,00%
70,00%
65,00%
60,00%
technical availability
0
50
100
150
200
250
300
production volume
AFO200

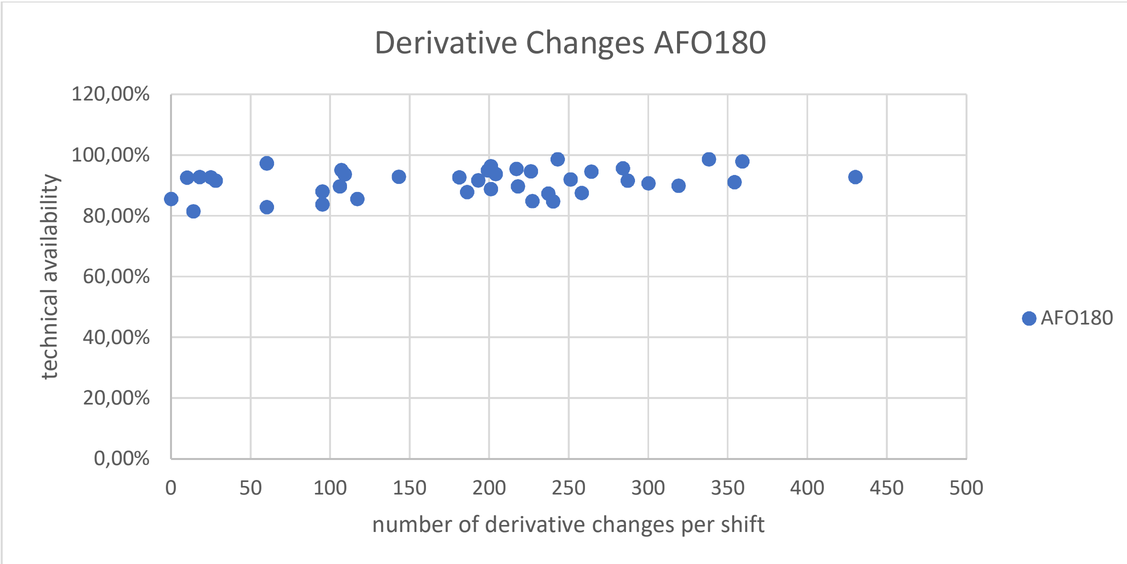

Production Volume AFO180
technical availability
105,00%
100,00%
95,00%
90,00%
85,00%
80,00%
75,00%
70,00%
65,00%
60,00%
0
50
100
150
200
250
300
350
400
450
500
production volume
AFO180

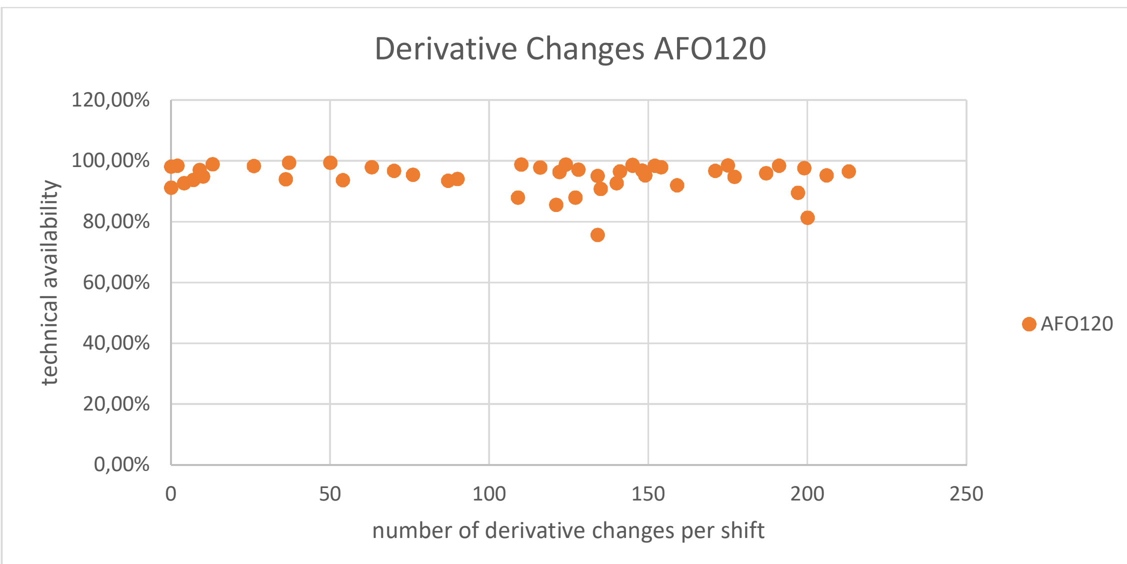

Production Volume AFO160
technical availability
105,00%
100,00%
95,00%
90,00%
85,00%
80,00%
75,00%
70,00%
65,00%
60,00%
0
50
100
150
200
250
300
production volume
AFO160

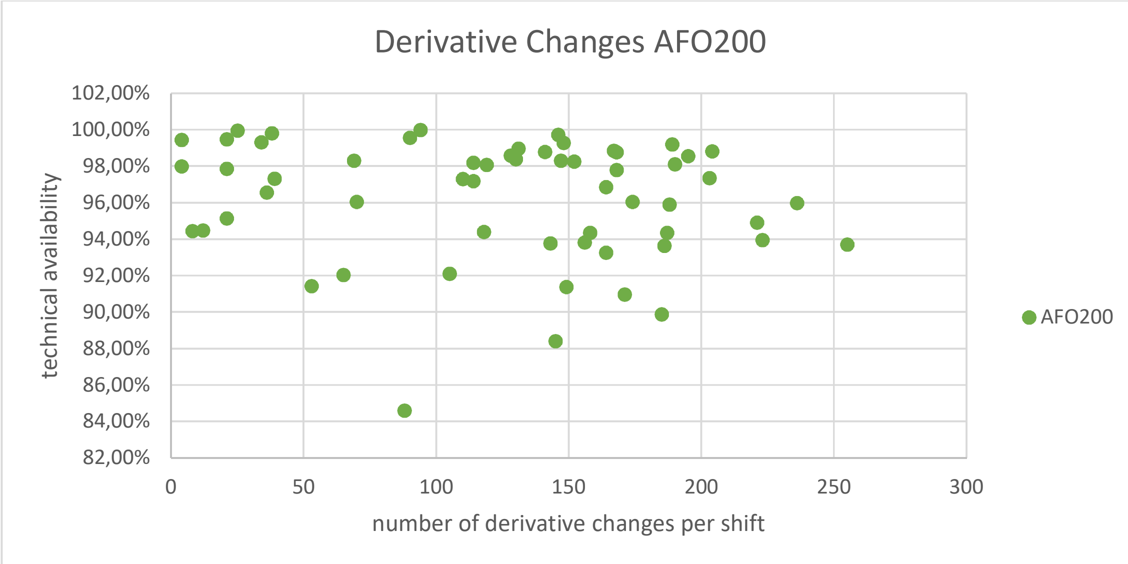
13.1.2 Cell Overview - Derivative Changes

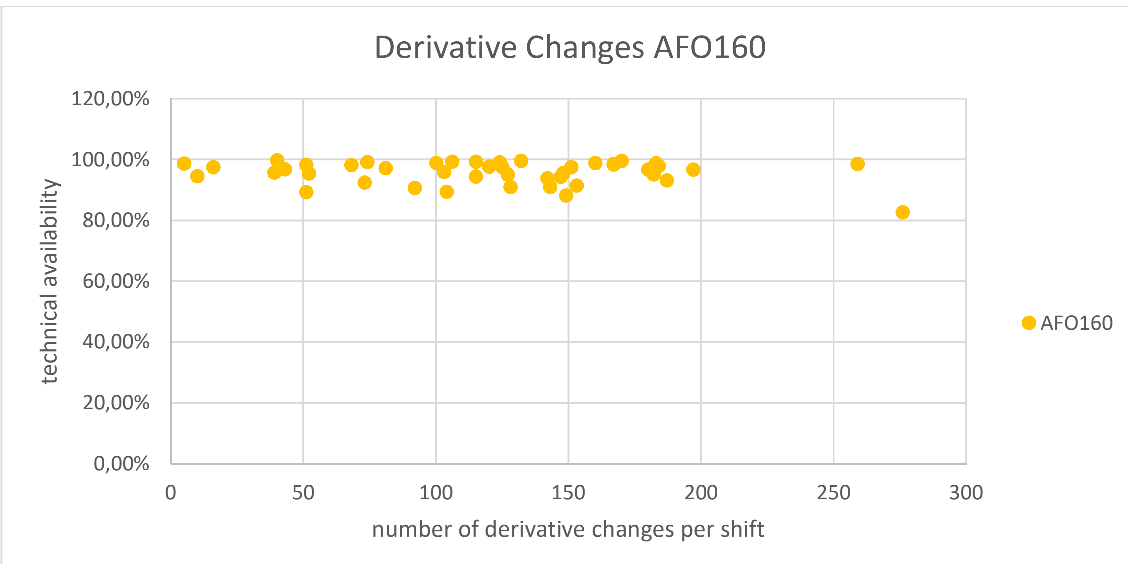





Derivative Changes AFO180
120,00%
100,00%
80,00%
60,00%
40,00%
20,00%
0,00%
technical availability
0
50
100
150
200
250
300
350
400
450
500
number of derivative changes per shift
AFO180


Derivative Changes AFO120
120,00%
100,00%
80,00%
60,00%
40,00%
20,00%
0,00%
technical availability
0
50
100
150
200
250
number of derivative changes per shift
AFO120


Derivative Changes AFO200
technical availability
102,00%
100,00%
98,00%
96,00%
94,00%
92,00%
90,00%
88,00%
86,00%
84,00%
82,00%
0
50
100
150
200
250
300
number of derivative changes per shift
AFO200


Derivative Changes AFO160
technical availability
120,00%
100,00%
80,00%
60,00%
40,00%
20,00%
0,00%
0
50
100
150
200
250
300
number of derivative changes per shift
AFO160

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