STUTTGARTER BEITRÄGE ZUR PRODUKTIONSFORSCHUNG

Petra Foith-Förster

»Design of matrix production systems for the personalized production of mechatronic machine modules«

Fraunhofer IPA

Universität Stuttgart

STUTTGARTER BEITRÄGE ZUR PRODUKTIONSFORSCHUNG BAND 153

Petra Catharina Foith-Förster

»Design of matrix production systems for the personalized production of mechatronic machine modules«

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Bibliographische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der
Deutschen Nationalbibliographie; detaillierte bibliografische Daten sind im Internet über
http://dnb.de abrufbar.

Zugl.: Stuttgart, Univ., Diss., 2022

D 93

2023

Druck und Weiterverarbeitung:
Fraunhofer Verlag, Mediendienstleistungen, Stuttgart, 2023
Für den Druck des Buches wurde chlor- und säurefreies Papier verwendet.

Design of matrix production systems for the personalized production of mechatronic machine modules

Von der Fakultät
Konstruktions-, Produktions- und Fahrzeugtechnik der Universität Stuttgart
zur Erlangung der Würde eines Doktor-Ingenieur (Dr.-Ing.)
genehmigte Abhandlung

Vorgelegt von

Dipl.-Ing. Petra Catharina Foith-Förster
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Datum der mündlichen Prüfung: 22.11.2022

Institut für
industrielle Fertigung und Fabrikbetrieb der Universität Stuttgart

2022

Preface

„Pure Vernunft darf niemals siegen“[1] sings the German rock band Tocotronic. This dissertation was created during my time as a researcher at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart. It certainly wasn't purely reasonable to pursue a PhD project whilst working mostly fulltime at Fraunhofer IPA and having three children at the same time. It was challenging and exhausting. But it was also a very interesting, good and fun time, with the possibility to learn lots in a very exciting working environment. And there is no better balance than family life.

I had formerly spent some years working in a factory environment of the Robert Bosch GmbH, where I got to know the design of lean production lines, their strength and advantages for an efficient production, but also their deficiencies in times of fluctuating volumes. As a responsible for production planning and control, I experienced first-hand the efforts it takes to handle even a small number of one product family's different variants on a coupled production line. With this experience in mind, I started off at Fraunhofer IPA to pursue the design of a production's organizational structure that kept the productivity of the production line, but delivers more flexibility to cope with the everyday challenges of production.

This dissertation wouldn't have been possible with the help and input of many.

Foremost I'd like to thank Prof. Dr.-Ing. Bauernhansl, director of the Fraunhofer IPA and the Institute of Industrial Manufacturing and Management IFF of the university of Stuttgart, for the supervision of the PhD project, for his inspirational ideas on innovative production systems, and especially for always providing me opportunities to take on new projects and roles at the institute. I equally thank Prof. Dr. Nam Pyo Suh, who is the Ralph E. & Eloise F. Cross Professor Emeritus at M.I.T., for the the co-supervision of the thesis, for the valuable advice and his thought-provoking questioning of my solution approach applying Axiomatic Design. Thanks also go to Prof. Dr.-Ing. Steffen Ihlenfeldt, who stepped in as an on-site co-supervisor for the final phase of the PhD. I have always enjoyed working with Steffen Ihlenfeldt on the topic of matrix production within the Fraunhofer network.

I further thank Michael Lickefett and Timo Denner, my superiors during my time in the department of Factory Planning and Production Management at Fraunhofer IPA,

[1] Pure reason must never prevail

for their open ears for discussion and their professional input, as well as likewise for the opportunities to take over responsibility within the department. My fellow research group leaders Dr. Klaus Erlach and Dr.-Ing. habil. Hans-Hermann Wiendahl helped me with fruitful discussions and Klaus in particular with a very detailed proofreading. Thank you as well!

Many thanks to all colleagues at Fraunhofer IPA for their joint efforts, the good working atmosphere and the successful project work. These thanks go especially to the colleagues of the Application Center I4.0's „Spitzenteam“, the core team of the business unit automotive, and even more to the colleagues of the group 121, Axel Bruns, Patricia Berkhan, Emir Cuk, Florian Grabi, Susann Kärcher, Daniel Ranke, Michael Trierweiler – it was a pleasure to be part of the team with you! My supportive office roommates Susann Kärcher and Dr.-Ing. Silke Hartleif are to be thanked for the uplifting chit-chatting and the intense peer-to-peer discussions of PhD contents.

I had the privilege to supervise many students, who either worked as research assistants or pursued their own scientific theses at Fraunhofer IPA. Their valuable assistance in our research and industrial projects provided me with necessary time needed to work on my PhD thesis. I specifically thank Melda Aygan, Constanze Reich, Claudius von Rohr and Jana Trstenjak for the digitalization of my hand-scribbled graphics.

Special thanks also go to all librarians of the Fraunhofer IPA library for their support in literature work, to Martin Hägele, former department head of Robot and Assistive Systems at Fraunhofer IPA, for introducing Axiomatic Design to me, and to my colleague Nico Güttler for his LaTeX-assistance.

I would like to further thank the Christiane Nüsslein-Volhard-foundation and the Fraunhofer Talenta program for their financial support, as well as the German Federal Ministry of Education and Research BMBF for the funding of the research campus ARENA2036, in which I laid the basic foundation of my PhD research.

Finally, a big thank you to friends and family for their motivation and for good times along the way. I deeply thank my parents Rosemarie and Dieter Foith for always supporting me and giving me all the opportunities to find my way. I also thank my parents, as well as my parents-in-law Antonie and Bernd Förster, for being great grandparents and helping out with looking after my sons when things got tight.

The biggest thanks go to my husband Christian, who not only equally shares our life with me, goes on adventures with me, and provides me with the necessary freedom to realize my ambitions, but always backs me up and believes in me. I am very grateful for his love and our beautiful sons Vinzent, Jost and Ferry.

Kurzfassung

Krisenbedingte Stückzahlschwankungen und die hohe Variantenvielfalt der personalisierten Produktion stellen eine Herausforderungen für Produktionssysteme dar. Diese müssen variantenflexibel, skalierbar und rekonfigurierbar sein und eine effiziente Produktion großer Stückzahlen ermöglichen. Die heute vorherrschende Produktionsstruktur der verketteten Linien kann dies in der Regel nicht leisten, da sie auf eine bestimmte Ausbringungsmenge und eine begrenzte Zahl an Produktfamilien ausgelegt ist.

Diese Arbeit liefert eine Methodik zur Gestaltung von Matrixproduktionssystemen. Matrixproduktionssysteme bestehen aus frei anfahrbaren Prozessmodulen, die durch einen flexiblen Materialfluss bedarfsbezogen verknüpft werden. Jeder Auftrag durchläuft einen eigenen variantenspezifischen Pfad durch das System. Durch ihren modularen Aufbau können Matrixproduktionssysteme eine Vielzahl an Montage- und Fertigungsprozessen in einem System vereinen. Die gemeinsame Nutzung der Prozessmodule durch verschiedener Produktfamilien ermöglicht eine hohe Auslastung investitionsintensiver Produktionsressourcen. Eine Skalierung der Ausbringungsmenge oder die Integration neuer Varianten ist durch funktionale Anpassung einzelner Prozessmodule oder durch eine Veränderung ihrer Anzahl mit geringer Beeinträchtigung des Gesamtsystems möglich.

Die Methodik baut auf den Prinzipien des Axiomatic Design auf. In einer prozessorientierten Vorgehensweise werden zuerst die Prozessmodule eines Produktionssystems funktional gestaltet und anschließend gemäß der Ausprägung von Wandlungshemmnissen für einen spezifischen Funktionsumfang spezifiziert. Zur Gestaltung eines Matrixproduktionssystems werden geeignete Prozessmodule produktionsprogrammspezifisch ausgewählt und gemäß des Kapazitätsbedarfs ihrer Funktionen in einem flussorientierten Layout instanziiert.

Die Methodik legt die Vorgehensweise der Gestaltung fest und liefert Produktionssystemmodelle und Gestaltungskriterien als Entscheidungshilfe für Produktionsplaner. Sie legt zudem Berechnungsvorschriften für die Auswahl von Lösungsalternativen im Gestaltungsprozess fest. Eine integrierte Bewertungsmethode erlaubt schließlich die Gegenüberstellung alternativer Entwürfe.

Die Erprobung der Methodik in einer Produktionssystemplanung eines Elektromotorenherstellers zeigt deren Anwendbarkeit und Wirksamkeit. Die Arbeit liefert damit einen Beitrag zur wettbewerbsfähigen Gestaltung von Produktionssystemen.

Abstract

Crisis-driven fluctuations of production volumes and the high number of variants in personalized production challenge production systems. To maintain their competitiveness production systems must be flexible, scalable and reconfigurable, and enable an efficient production of high volumes. Today's prevalent mix-model production lines are dedicated to certain output quantities and a limited number of product variants. They are insufficient for personalized production in a turbulent business environment.

This thesis provides a methodical system for designing matrix production systems. Matrix production systems consist of flexibly-linked process modules which are linked by a material flow only on demand. Each order pursues its own variant-specific path through the system. Due to their modular design, matrix production systems are able to integrate a variety of assembly and manufacturing processes to produce different product families in one system. The shared use of the process modules by a wide range of variants enables high utilization of investment-intensive production resources. A scaling of the output quantity or the integration of new variants is possible by functional adaptation or alteration of quantity of individual process modules with little impact on the overall system.

The design method of the methodical system is based on the principles of Axiomatic Design. In a process-oriented approach, the process modules of a production system are first designed functionally and saved in a knowledge base for subsequent production system design projects. The process modules are specified for a specific functional scope according to the quantification of change barriers. To design a matrix production system suitable process modules are then selected for a specific production program and instantiated according to the capacity requirements of their functions in a flow-oriented layout.

The methodical system specifies the design procedure and provides production system models and design criteria as decision support for production planners. It also specifies calculation rules for the selection of alternative solutions in the design process. Finally, an integrated evaluation method allows the comparison of alternative overall designs.

The applicability and effectiveness of the methodical design system was validated with a production system design project at an electric motor manufacturer. This thesis thus makes a contribution to the competitive design of production systems.

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Acronyms

AD	Axiomatic Design
AGV	Automated guided vehicle
AI	Artificial Intelligence
ARENA2036	Active Research Environment for the Next Generation of Automobiles
ARIS	Architecture of Integrated Information Systems
Axiom 1	Independence Axiom
Axiom 2	Information Axiom
BAZ	General purpose numerically controlled machining center
BMS	Biological Manufacturing Systems
BOA	Utilization-oriented order release concept
BOM	Bill of Materials
BPMN	Business Process Modeling Notation
C	Design constraints
CA	Customer Attribute
CAM	Computer-Aided Manufacturing
CEME	Collectively Exhaustive and Mutually Exclusive
CNC	Computerized Numerical Control
ConWIP	Constant work in progress
CPS	Cyber-physical system
DP	Design Parameter
EER	Enhanced Entity-Relationship Diagram
eFFBD	Enhanced Functional Flow Diagram
EPK	Incident-oriented Process Flow
ER	Entity-Relationship Diagram
FFBD	Functional Flow Diagram
FIFO	First-in First-out
FMS	Flexible Manufacturing System
FR	Functional Requirement
FSZ	Concept of cumulative quantity
GDP	Gross Domestic Product
GVA	Gross Value Add
HMS	Holonic Manufacturing Systems
I	Information content
I4.0	Industrie 4.0
ICT	Information and Communication Technology
IDEF	Integrated DEFinition
IMS	Intelligent Manufacturing Systems
iPeM	Integrated product development model
IT	Information Technology
KPI	Key Performance Indicators
MAAS	Mobility as a Service
MTO	Human-Technology-Organization
MVM	Munich Procedurale Model
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OPT	Optimized-Production-Technology
PAP	Program Workflow Diagram
PM	Process Module
PPC	Production Planning and Control
PV	Process Variable
RAMI4.0	Reference Architecture Model Industrie 4.0
RAS	Reconfigurable Assembly Systems
RMM	Reconfigurable Multi Technology Machine
RMS	Reconfigurable Manufacturing System
RMT	Reconfigurable Machine Tool
ROI	Return on investment
SA/SD	Structured Analysis/Structured Design
SCC	System Control Command
SD	Standard Deviation
SME	Small and Medium-sized Enterprise
SOO	Sequence of production operations
STEP	Standard Exchange Product Model Data
SysML	Systems Modeling Language
TRIZ	Theory of Inventive Problem Solving
UML	Unified Modeling Language
WIP	Work In Process

1 Introduction and scope

Manufacturing companies need to prepare for change in order to stay competitive and prosper (Bauernhansl et al. 2020, p. 24; ElMaraghy et al. 2009, pp. 3–6; Zäh et al. 2005). They operate in turbulent ecosystems of intensified speed and scope of change (Pawellek 2014, p. 121; H-P. Wiendahl et al. 2014, p. 10; Soder 2014, p. 85; Westkämper 2007, p. 4; Warnecke 1996, p. 20). Personalized production replaces mass customization (Koren 2010, p. 32), and changeable production systems are a competitive necessity for adjusting to the challenges of this new production paradigm (Schenk et al. 2014, p. 18; Abele et al. 2011, p. 37; Koren 2010, pp. 32–39; Westkämper et al. 2009b, p. 1; H-P. Wiendahl et al. 2007, pp. 783, 796).

1.1 Initial situation

The turbulences in economic ecosystems trace back to so-called megatrends. Originally identified by Naisbitt (1984) as larger underlying patterns of emerging societal developments, megatrends transform the business environment and spark *change drivers* which destabilize production systems. In other words, they are exogenous and endogenous factors that pressure organizations to change. (Westkämper et al. 2016, pp. 54–56; Westkämper et al. 2009b, pp. 9–12; H-P. Wiendahl 2002, pp. 124–126; H-P. Wiendahl et al. 2002, p. 133)

Westkämper et al. (2016, pp. 51–54) identify a *growing world population*, *globalisation*, *individualization*, *highly dynamic economic cycles*, and *knowledge and information technology* as current megatrends with a significant impact on production. The *growth of the world population* results in an increasing demand for industrially produced goods but also in a shortage of resources forcing higher efficiencies (Westkämper et al. 2016, p. 51). *Globalization* manifests in product feature regionalization with a respectively higher number of product variants (Koren 2010, p. 33). This conforms with the trend of *individualization* as the most-prominent driver of production system change (Westkämper et al. 2016, p. 53; Schirrmeister et al. 2003, p. 87). The corresponding adjustment from satisfying supply-oriented markets to demand-driven, market-oriented production is accompanied by smaller lot sizes and by specialized materials and processes. Besides, a significant variety of manufacturing technologies, new innovative and conventional ones alike allow for the necessary customization of product configuration and customized parts (Westkämper et al. 2016, pp. 52–53). *High dynamic economic cycles* require short-term return on investment (ROI) (Westkämper et al. 2016, p. 53). *Information and Communication Technology (ICT)*, finally, can be seen as an enabler to master the challenges of change.

The impact of these megatrends is effectively visible in economic indicators and statistical production investigations. The industrial production index, showing output and activity of the industry sector, has constantly been growing worldwide in the last decades (Figure 1.1, upper left diagram)[2]. Temporary drops in the trendline due to economic crises are clearly visible in the data. Against the commonly held perception of a general increase in market volatility, however, a higher absolute fluctuation of production volumes is not traceable between crises. This is, for instance, evident in the variance of the German 1998-2021 month-to-month production index change (Figure 1.1, upper right diagram)[3], as a measure of production volume variation. With the exception of the Covid-19 pandemic, the standard deviation (SD) of the exemplary production index change has been dispersing constantly between 0.06 and 0.12. This means, that even though production volumes fluctuate, the amplitudes of these fluctuations have not increased in recent decades. Studies, however, show that intervals between economic crises have been shorter in recent decades (McKinsey 2010, p. 21). Consequently, production systems need to be able to follow a product's lifecycle and seasonal as well as day-to-day shifts of production volumes to the same extent as in former decades. Furthermore, production systems need a general capability for structural upscaling and the possibility to downscale abruptly in times of crisis gives a competitive edge to manufacturers.

Equivalent to the production index labor productivity has risen in the last decades (Destatis 2020, p. 50)[4]. Such an increase of productivity is achieved by measures of optimization and rationalization in the areas of technology, organization, and applied methods (Löffler 2011, p. 3). It is associated with a higher degree of automation, but it also indicates that today's production equipment shows a higher volume throughput capability per time unit than in recent decades. This creates a considerable challenge, as product variants have increased significantly over the same period, which means that production equipment needs to be disproportionally flexible with regard to different product variants.

[2] Data for Germany, USA and EU28 has been retrieved from OECD (2020). World data has been retrieved from the World Bank (2021a). Filters were set on manufacturing only and on time period 1990-2019.

[3] To determine the variance of the production index, the differences between consecutive monthly production index values were calculated for each month. A twelve-month rolling standard deviation was then determined of each month's difference to its consecutive month in relation to six monthly differences prior and six monthly differences following this month. Production index data for the calculation was retrieved from Destatis (2020).

[4] Labor productivity is given by the ratio between the GDP and number of people employed or hours worked in the same time period (Destatis 2020, p. 50).

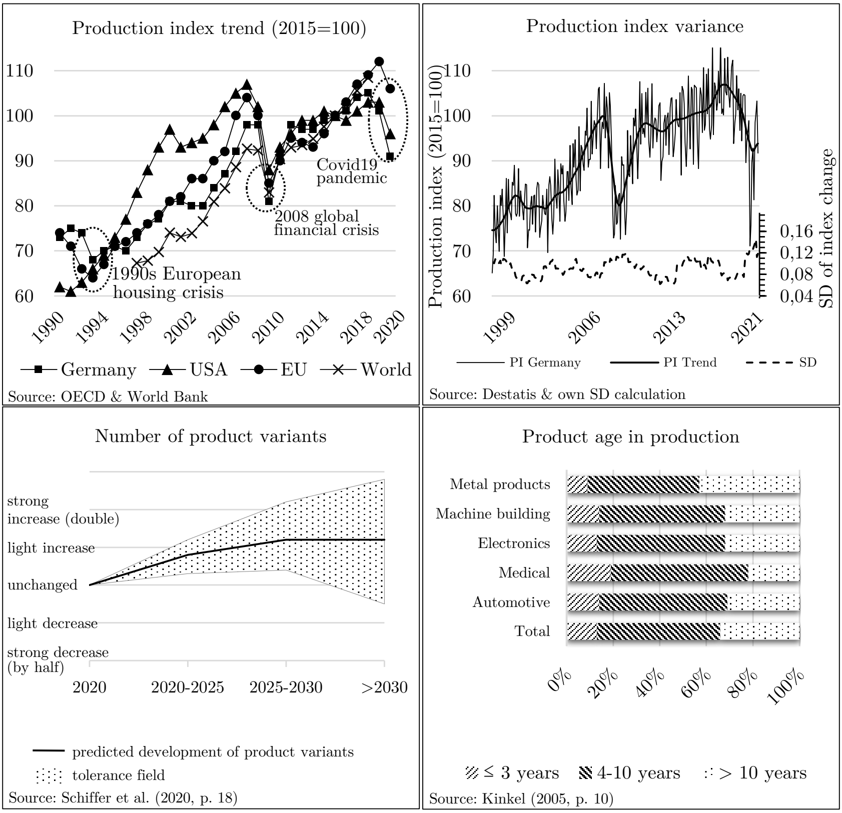


Figure 1.1: Economic and product variety indicators

Surveys conducted in industry show an increase of offered product variants in past decades and predict the continuation of this trend in the future. Kinkel (2005, p. 3) points out that 75% of all surveyed companies raised their offered variants in the ten years previous to 2005. Variants in the medical, electronics, and the automotive industry added above average to this percentage[5]. Schiffer et al. (2020, p. 18) show that a light increase is expected across all industries (Figure 1.1, lower left diagram). Using a predictive perspective as well, Luckert at al. (IHK 2018, p. 27) particularize that 73% of automotive and machine-building OEMs and first-tier suppliers plan to raise or even double the number

[5]Vehicle derivatives tripled worldwide since the 1960s (TAB 2012, p. 137). Automotive models doubled since the 1990s (Dudenhöffer (speech on the IAA automotive fair 2006), cited in Hüttenrauch et al. (2008, p. 121)).

of their physically offered variants until 2023, while still 65% of second- and subsequent-tier suppliers and 58% of equipment suppliers expect to do so.

A modular product architecture has been identified as one of the key enablers for manufacturing companies to offer a higher number of product variants (TAB 2012, pp. 141–145; Watanabe et al. 2004, p. 573). The automotive industry already pursues modularization with platform design (McKinsey 2013, p. 11). In the special machinery building industry, a reduction of product variety in production is expected in the short term (VDMA et al. 2014, pp. 41, 62; maexpartners et al. 2014). The explanation for this seemingly contradictory development lies in the concept of modularization as well. The sector seeks to increase its product variety offer to its customers, but is generally less advanced in standardization (Oliver Wyman 2016, p. 30). When implementing modularity in product design, catch-up effects will reduce variety in production. A production system capable of producing modular products is nonetheless needed.

In the automotive industry, the trend of Mobility as a Service (MAAS)[6] will potentially slow down the extend to which the number of offered vehicle variants increase through fleet formation of MAAS providers. Nevertheless, privately owned cars are expected to still account for approximately 60% of all individually-driven journeys in Europe and in the US, and for approximately 45% in China (PwC 2017, pp. 24–25; McKinsey 2020). It is assumed that specifically autonomous private vehicles will tend to be large cars from the premium sector (PwC 2017, p. 21) that customers want to potentially configure individually. Furthermore, MAAS providers are predicted to serve different segments, with fleet vehicles of different sizes and configurations (PwC 2017, p. 21). All in all, MAAS will result in a certain standardization, but will not generally put an end to an ongoing progressive vehicle differentiation.

Hand in hand with the general increase of product variants goes the reduction of lot sizes. A comparison of passenger car models in the German market with new registrations in the same region shows an increase of models by 82% within ten years (CAR 2018). The total registration numbers have stagnated in the same time period around 3.3 million new cars each year (KBA 2017). Again, due to MAAS, a further reduction in the overall vehicle fleet is assumed (PwC 2017, pp. 31–32). Contrary to this trend, only about 1/3 of machine building and electrical industry representatives polled by Kinkel (2005, p. 4) report an actual decrease of production lot sizes. Production lot sizes strongly depend on lot size formation strategies, defined by Production Planning and Control (PPC). However, the trend of personalization is expected to lead to unique products, individualized by a customer and ordered in a lot size of one (Koren 2010, p. 33), which makes lot size

[6]MAAS is predicted to gain markedly in importance (PwC 2017, p. 24), the more so as autonomous vehicles are expected to have a strong positive impact on sharing concepts (PwC 2017, p. 20; Ruess et al. 2020, pp. 32–33).

formation and the sequencing of a variant mix difficult. Quantities are spread over a greater number of variants, which also makes a prediction of quantities more complex, even though there is no general increase in day-to-day volatility, as outlined above.

Finally, the documented decline of the first useful service life of consumable goods (UBA 2016) cannot be verified for the machine-building and automotive industries anymore (Kinkel 2005, pp. 9–10). Even the life cycle of the VW Golf model, often cited as an example of a reduced passenger-car life cycle (Wemhöner 2006, p. 47; Schuh et al. 2005, p. 152), has increased to seven years again, with the launch of the Golf VII in 2012 (VW-classic 2017). The production life cycles of all other German luxury class vehicles have consistently lasted six to eight years in recent decades (VW 2017; Porsche 2017; BMW 2021; Daimler 2021). But there is a significant gap between product life cycles and the usually much longer usage time spans of machines, tools and technological processes (Wirth 2002)[7]. And, the survey of Kinkel (2005, p. 10) indicates that several product generations are built in parallel, since sales are generated from old and newly developed products at the same time (Figure 1.1, lower right diagram). Product generations are consequently another driver for product variety in production. Processes and equipment must allow for the production of multiple product generations (ElMaraghy et al. 2009, p. 6). All in all, the utilization of production equipment with certain dedicated product variants becomes unlikely. As a consequence, a ROI on production machines and equipment is likely to require several variants and product generation, which bears a high risk of misinvestment. Investment needs to pay off very quickly, or it must be possible to invest step-by-step, following the actual market demands, instead of investing up-front into an unknown future development.

These above-described megatrends prevent a near end of the identified challenges: There are consequently six general objectives for the design of production systems, so that they are more resilient against crises and are able to stay competitive in today's turbulent business ecosystem:

- High productivity at a lot size of one
- Volume scalability (structural expansion & reduction)
- Product flexibility (of product variants, product families, and product generations)
- Sequence mix flexibility of product variants
- Capability to integrate new product generations, and associated technologies
- Possibility of gradual investments, following market demands

[7] Cited in Schenk et al. (2014, p. 148).

1.2 Problem statement

The previously effective production paradigm of mass customization is associated with flexible systems and lean manufacturing principles (Koren 2010, p. 37).

In machining, Flexible Manufacturing System (FMS) are multi-CNC-machine systems connected by an automated material handling system, which allows for a flexible sequence of operations (H-P. Wiendahl et al. 2014, pp. 180, 184; Günther et al. 2012, pp. 17–19). FMS are built with an a-priori flexibility towards similar parts (ElMaraghy 2005, p. 262). They allow for an automated machining of a defined group of parts with different cycle times without sequence restrictions (H-P. Wiendahl et al. 2014, p. 94). FMS are neither flexible beyond the defined range of parts in terms of product variety (H-P. Wiendahl et al. 2014, p. 184), nor do they provide volume flexibility to respond to unexpected demand changes. A scale-up of volume can only be achieved by adding more of the same machines in parallel (Koren et al. 2010, p. 1; Koren 2007, p. 34). The development towards general purpose numerically controlled machining centers (BAZs)[8] aims for the complete machining of parts on one machine (Ellermeier et al. 2002, p. 10). This is economically limited, as the higher flexibility of BAZs results in reduced productivity (Weck et al. 2005, p. 411). Recent developments trend towards Reconfigurable Multi Technology Machines (RMMs), with a modular setup, so that at least an adaptation to a different product spectrum is made possible (Abele et al. 2004, p. 152; Abele et al. 2007, p. 327).

The prevalent flexible system architecture related to assembly is that of a lean, mixed-model flow production line, often with rigidly linked stations and with a defined cycle time (Günther et al. 2012, pp. 13, 92). This setup is highly vulnerable to productivity and quality losses if operated outside of the tight, pre-defined flexibility range of volume and product variety (MacDuffie et al. 1996, pp. 366–368; Fisher et al. 1999, p. 785). Assembly is very much affected by the increase of product variety and market turbulences, due to its proximity towards the customer as one of the last links in the value-creation chain with upstream decoupling points (Reichwald et al. 2016, p. 211; Gagsch et al. 2001, p. 37; März et al. 2001, p. 3). Furthermore, the diversity of processes and tools is often higher in assembly than in machining, making process integration into one machine or station difficult - a fact that becomes manifest in the relatively lower degree of automation in current assembly systems. The use of general-purpose assembly stations is accordingly restricted, at least if a certain degree of automation is pursued.

The architecture of a coupled production line does not allow for a varying sequence of assembly processes (Günther et al. 2012, p. 16). Classical lean line design takes the product architecture as the first input of the design process, followed by a balancing to a

[8] In German, BAZ are referred to as *Bearbeitungszentrum*, which literally translates to *machining center*.

fixed cycle time (Günther et al. 2012, p. 92). The approach cements a system's product variety capability to a certain product architecture, which defines the possible sequence of assembly operations and a certain production output. Possible product variety is accordingly limited to variants of very similar product architectures[9]. The balanced cycle time, together with the spread of work content between different variants inherently leads to a loss of productivity for the mixed model flow line's designated spectrum of variety (Günther et al. 2012, p. 17; Swist 2014, pp. 13–54). The sequence of operations (SOO) and the defined output restrict the subsequent process design of the line. Hence, mixed-model lines are designed for a product variety within very few product families, and great effort is taken to compensate variants of low work content with variants of high work content in a controlled sequence, sometimes referred to as *pearlchain* (Dörmer 2013, pp. 40–41; März et al. 2011, pp. 135–139; Rekiek et al. 2006, pp. 94–102; Graf 2007, pp. 431–432; Fisher et al. 1999, p. 772). So, not only the overall product variety of a mixed-model line is limited, but also its product mix flexibility.

Beyond of what working time models provide, a scaling of volumes on a production line is only possible with a change of cycle time. This, in turn, is difficult and pre-requisites idle stations within the flowline (Steegmüller et al. 2014, pp. 103–104). Short-term changes (to follow, e.g., a seasonal curve) often fail, if not due to structural limitations of the workplace system, then due to an inflexible material supply. Other than that, a fundamental change of volume on production lines is only possible by duplication or elimination of the line as a whole. Lean, U-shaped assembly cells attempt to solve the problem of limited scalability with different line-balancing scenarios, self-organization of workers, or the approach of the rabbit chase in which workers assemble a complete product while following each other through the stations of the line (Takeda 2006, p. 101). However, this only works if operators are able to overtake each other, and if the number of workers in the line is considerably smaller than the number of stations so that there is no loss of productivity due to operators waiting for other operators to finish a variant of higher assembly content. All in all, production lines are often built larger than needed in the first place, resulting in largely underutilized production capacities (Koren et al. 1999, p. 528).

The alteration of the classical segmentation of machining and assembly system into a variant-neutral segment (called production pre-stage) and a variant-specific segment (called final production stage), proposed by Große-Heitmeyer et al. (2004, pp. 31–39), Mühlenbruch et al. (2003, p. 186), Lotter (2012b, p. 318), and H-P. Wiendahl (2004), limits the problem to the variant-specific segment but also intensifies it there. The contrary proposal, to move variety into pre-assembly areas in order to achieve nearly variety-free

[9] The setup of a line with non-clocked material flow and material buffers between stations does eventually allow for a bypassing of stations but does not allow reflows (Günther et al. 2012, pp. 16, 100).

main assembly lines (Aisenbrey et al. 2015, p. 15; Küber 2017), only shifts the problem to supplying assembly systems. Neither of the two approaches solves the lack of volume scalability.

Under the term of dematerialization (Schirrmeister et al. 2003, p. 42), the generation of product variety by software has been pursued. The trends of digitization, servitization, connectivity and software-intensive products lead to new business models, with smart products as platforms to deliver services to the customer throughout the lifecycle of the product (Harzenetter 2014). A study in 2018, however, showed that less than one-third of all interviewed companies in the automotive and machine-building industry manage to control their variety through software variants so far (IHK 2018, p. 28). And, even though it will be outlined in this thesis (Section 2.2) that approaches to manage the increase of product variety with product modularization and standardization of parts establish the basis for personalized products, these do not lead to a smaller spread of work content. Thus, there are limitations to solving the problem by focusing solely on product design.

In summary, RMM and BAZ are limited to machining technologies, expensive and only scalable to a limited extend. Lean production lines are specialized on a limited number of certain variants and only operate productively within a certain range of output. Therefore, it can be concluded, that the production paradigm of mass customization and its prevalent organization structures of RMM and BAZ workshops and flexible lean production lines are not suitable to tackle the challenges of today's production.

The emerging manufacturing paradigm of personalized production promotes reconfigurable production systems for a variable demand of unique, customer-individualized products (Koren 2010, p. 36). Preliminary analyses applying discrete-event material flow simulation to automotive assembly showed a promising increase in labor productivity through modular, reconfigurable production systems (BCG 2018, p. 11). It was found that the functional segmentation strategy to define the process capabilities of system stations is a major influencing factor in the overall productivity and changeability of such a reconfigurable system (Foith-Förster et al. 2017). A purely technology-oriented job shop definition of functional capabilities does not succeed, as losses due to necessary transports between different stations are too high. Modularization by simply decoupling a lean flow line's stations eliminates the sequence restriction. However, it adds waste due to higher material buffer and transports, and process modules' capabilities are then still restricted to dedicated variants. There are currently no production system design approaches available to design modular reconfigurable production systems for a personalized production in a turbulent business ecosystem. Design methods are needed which address the functional process requirements of a production system explicitly while aiming at the six general characteristics of a competitive personalized production system, stated above (Section 1.1).

1.3 Objective and guiding research question

The objective of this PhD project is to develop a methodical system to design personalized production systems of mechatronic machine modules. The methodical system shall enable a system designer to develop a modular production system for industrial production, which will be called matrix production system. The methodical system is primarily applicable in a situation where there is high prevailing product variety or high instabilities regarding future developments of products and production volume, which makes a lean, mixed-model flow line design impossible or economically infeasible. The guiding research question of this dissertation is:

How can matrix production systems be designed so that they meet the requirements of personalized production?

To constitute a solution space, the research question shall be explored on the basis of two main hypotheses:

Hypothesis 1 A modular setup of flexibly linked process modules with variable cycle time is a suitable system structure paradigm for personalized production (Figure 1.2, left graphic).

Hypothesis 2 A process-driven design approach is suitable for personalized production systems (Figure 1.2, right graphic).

Table 1.1 summarizes the result, scope, and solution space of the methodical design system[10]. The matrix production system shall have a modular architecture. Flexible linking of process modules enables easier reconfiguration of the overall system. Moreover, functional process capabilities can be allocated to system elements without a previous product family segmentation. In principle, the design of general-purpose equipment is possible with a process-oriented combination of operations.

Result	Scope of Application	Solution Space
High productivity	Production system design	Modular architecture
Lot-size-one capability	Manufacturing & Assembly	Flexible material flow
Low operative complexity	Individualized products	Process-driven design
Flexibility	Mechantronic modules	Use-case-related validation
Reconfigurability	High-volume production	

Table 1.1: Objectives of the dissertation

[10]Table structure (result, scope of application, solution space) derived from Bauernhansl (2003, p. 10).

In consideration of the characteristics of a competitive personalized production system (Section 1.1) the result must be a highly-productive lot-size-one-capable system . The resulting design shall further follow a quest for low operative complexity, to enable a straightforward operation of the system. At the same time, the system must be highly flexible towards existing variants. As the overall variation of day-to-day production volumes has not increased in general, it is assumed that existing degrees of freedom for production volume variation enabled by working time flexibility are appropriate to cover a day-to-day variation as long as the system shows a high enough product mix flexibility. Reconfigurability of the system in order to integrate future products and technologies, in order to scale the volume to different production volume ranges and in order to make investments step-by-step following actual needs instead of upfront prediction of future developments, is, however, essential. So, an overall maximization of system changeability is pursued.

The method concentrates on the direct areas of production as the actual point of value creation. Processes and production technologies are selected by the demand of personalized production. Primarily, assembly technologies are the scope of this dissertation. Lot-size-one-capable machining and additive manufacturing technologies are considered for the individualization of parts. Regarding the product and industrial sectors, the method shall be tailored for the design of production systems of mechatronic machine modules in high volumes. This scope of application is justified in two ways: First, the product architecture must allow personalized production. Discrete products of modular architecture are required. The trend of ICT also manifests in product design. Today, most machine modules are mechatronic systems. Second, the trend to transfer variety away from main assembly lines and the limited options of system suppliers to move variety back to their OEMs (IHK 2018, p. 28) puts, in the short-term, most of the strain to pre-assembly systems and first-tier suppliers where modules are produced.

1.4 Classification according to the philosophy of science and outline of this dissertation

In the philosophy of science, engineering science is classified as factual science (Bunge 1998, pp. 24–26). Factual sciences seek to describe, explain, and design an empirically observable part of reality (P. Ulrich et al. 1976a, p. 305). They are demarcated from formal sciences by their synthetic (versus purely analytic) character (Carnap 1935, p. 35). Formal sciences, such as mathematics, logic and philosophy, pursue the development of sign-system notations and rules for their proper implementation (P. Ulrich et al. 1976a, p. 305).

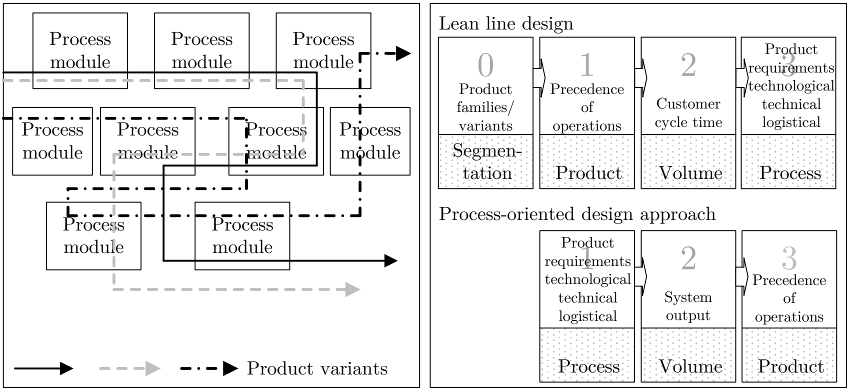


Figure 1.2: Modular architecture of flexibly linked process modules (left) and comparison of classical lean line design and process-oriented design (right)

Factual sciences are further detailed into the research types of (pure) basic and applied research. Basic research seeks to construct explanatory models[11]. It is often associated with the natural sciences. Applied research has the function of analyzing human action alternatives. It creates social and technical systems for practical use. (P. Ulrich et al. 1976a, p. 305)

Pure basic and applied research should, however, not be understood as dichotomous (Stokes 1997, p. 72): Engineering sciences are positioned in between the scientific research types of basic and applied science (Schuh et al. 2013, p. 34)[12], pursuing a use-inspired quest for fundamental understanding (Stokes 1997, p. 73). They use fundamental and applied concepts with a bias dependent on the respective scope of research. While social science empirically gains (scientific) knowledge the focus of technical engineering science lies in conceptional constructive research (Schuh et al. 2013, p. 36; J. Müller 1990, p. 8). Reality emerges from conceptual design (Lenk 1979, pp. 189–190)[13].

Due to the objective to develop a system of production system design methods, the research work of this dissertation belongs to factual science with a strong focus on applied research (Figure 1.3). Formal notations are used to model the production system and to structure the design process. This is in line with Ulrich et al.'s understanding that it is impossible to do empirical research without utilizing formal science (1976a, p. 306).

[11] Explanatory models of basic research are deducted from a theory context to describe a very specific aspect of reality (H. Ulrich 1984, p. 173).

[12] Schuh et al. follow Zohm (2004, p. 6) and Bauernhansl (2003, p. 12) in their categorization of engineering science. P. Ulrich et al. (1976a, p. 305) have formerly seen it, together with social and business sciences, as applied science only.

[13] Cited after H. Ulrich (1984, p.174).

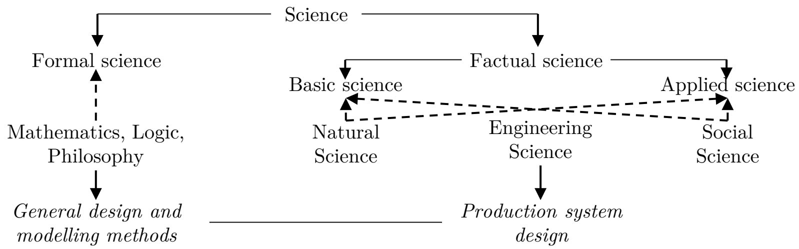


Figure 1.3: Scientific categorization of this dissertation (according to P. Ulrich et al. 1976a, p. 305)

1.4.1 Research methodology

Research methodologies of applied science differ by their approach to problem solving (Schuh et al. 2013, p. 72). The critical rationalism of Popper is probably the most reputable representative of deductive problem solving. Popper (2005, p. 9) argues that it is impossible to experimentally prove the truth of a theory, whereas falsification is possible by a single counterexample. Consequently, any hypothesis needs to be falsifiable by the observation of reality, making observation pivotally important (H. Ulrich 1984, p. 174). Popper's predominant focus is the validation of hypotheses (Kubicek 1977, p. 7). He shows no interest in the discovery context of scientific findings (Ropohl 2009, p. 333).

Kubicek, on the contrary, solves problems inductively. He draws hypotheses from the scientist's presuppositional knowledge with critical reflection on reality in iterations (Kubicek 1977, pp. 17–19). Kubicek's heuristic frame of reference allows for a criticisable research process: Inter-subjective transparency is brought into the discovery context of research by disclosing the inevitable subjectivity of the researcher (Rößl 1990, pp. 100–101).

Lakatos (1974), P. Ulrich et al. (1976a, 1976b), Feyerabend (1978), H. Ulrich (1984) and Tomczak (1992) subsequently combine deductive and inductive elements in their research methodologies (Schuh et al. 2013, p. 72; Töpfer 2010, p. 119). P. Ulrich et al. (1976a, p. 306; 1976b, p.348) divide the research process into terminologically-descriptive, analytically-deductive, and empirically-inductive activities and introduce discovery context, rationale context, and usage context for problem solving in the domain of factual science.

While Popper's critical rationalism provides a solid basis, applied science needs induction for its constructive nature. In the quest for rigor and relevance alike, practical usage must be considered, and high scientific standards must be followed. H. Ulrich's structural research process (H. Ulrich 1984, p. 193) originates and ends in the consideration of practice and integrates the research methodology of P. Ulrich et al. (1976a, 1976b) (Schuh et al. 2013, p. 43). Since this is the most holistic approach, this dissertation's research process will be organized accordingly (Section 1.4.2).

1.4.1.1 Discovery context

The discovery context accommodates that scientific discoveries can never claim endless universal truth. Science happens inside of a sociocultural framework constructed by the expertise and experience of the scientist (1), the given society's set of norms and values (2), the paradigm[14] followed by the faculty (3), and the state of the art of factual and formal sciences (4). Consequently, there is no absolute validity of scientific work, but only a validity in respect to the purpose-driven choice of scientific approach. (P. Ulrich et al. 1976a, pp. 305–306)

(1) Through her first employment as a production system designer and logistics manager at the Robert Bosch group, the author developed a profound lean expertise and experienced first-hand the difficulties of integrating a high number of variants into clocked assembly lines, both from a design and from an operative PPC perspective. At Fraunhofer IPA, the author concentrated on flexibility, changeability and digitalization in factory planning. Considerable parts of this PhD project have been developed within the BMBF-funded research project ARENA2036 (Bauernhansl 2014a, pp. 274–276), considering the requirements of the automotive OEM and component supplier members of the consortium. Preliminary results of the design method were tested by the author in various industry projects.

(2) The author believes in the appropriateness of a social market economy. The underlying capitalist economic model values competition between market actors (Suchanek et al. 2017) and seeks for scientific and technological advances as a norm (EU 2007/C 306/1 2007, Art.2, §3). The project's underlying intention is, respectively, to enable the design of competitive, changeable and technologically progressive production systems.

(3) Guiding theories incorporating scientific paradigm capability exist with a theoretical or practical constructive focus in the domain of industrial engineering sciences (Siemoneit 2010, p. 169)[15]. Due to this dissertation's strong bias on applied science, only paradigms with a design focus are applicable[16]. According to P. Ulrich et al. (1976a, p. 308-309) and

[14] Paradigm stands for school of thought. It defines what is predominantly considered to be true by the faculty. (T. Kuhn 2014, p. 25)

[15] Siemoneit calls his thesis *Philosophy of Science for Business Studies*, but puts a strong focus on technology sciences. This makes it an adequate source for scientific paradigms relevant to industrial engineering sciences with an applied science bias.

[16] This excludes paradigms with a theoretical focus, such as the theory of control parameters of Gutenberg (1951) (called *Faktortheoretischer Ansatz* in the German original (P. Ulrich et al. 1976a, p. 308)), the behavioral theory of Schanz (1977), quantitatively-descriptive theories, game-theory, and New Institutional Economics (NIE) theories. They are all described in detail by Siemoneit (2010, pp. 170–185).

Siemoneit (2010, pp. 179–185) these are H. Ulrich's systems theory (1984), E. Heinen's decision theory approach (1971), and Steinmann's activity-oriented approach (1978).

Systems theory understands business companies as dynamic, open, complex, and socio-technical[17] systems of economic purpose (H. Ulrich 1971, pp. 47, 60; H. Ulrich 1984, p. 37). It seeks to describe both static and dynamic operational behavior of a system by its elements and their relations (H. Ulrich 1971, pp. 45, 49–52). The approach enjoys great popularity in the field of applied and design research (Siemoneit 2010, p. 180) and aligns with this dissertation's understanding of a production system. The design of a production system is furthermore a decision-intensive process. Choices among different alternative design solutions are taken under uncertainty[18], as the actual values of a future production program are unknown, especially in the turbulent environment associated with personalized production. To foster the designer's decision-making, a comparison of alternative design solutions needs to be facilitated. System theory lacks the necessary precision to accomplish this as a standalone paradigm[19]. Decision theory focuses on the decision-making-process during a system design in its focal point (E. Heinen 1971, p. 22; P. Ulrich et al. 1976a, p. 309). Decisions are derived on the basis of normative explanatory models, revealing the effects of different states of influencing factors on alternative choices (P. Ulrich et al. 1976a, p. 309). The activity-oriented approach, on the other hand, is only applicable to weigh alternative options for action within a given system, under allocation of scarce good (Siemoneit 2010, pp. 183–184). Therefore, systems theory and decision theory together form the scientific paradigm of this project.

(4) The author's understanding of system design has formatively been influenced by Suh (2001) and his top-down axiomatic design paradigm, as well as by the definition of technical design by J. Müller (1990, p.8-12). J. Müller's fundamental work on problem-solving also provides the basis of this project's method development (J. Müller 1990, p. 12). Furthermore, the generic theory of models by Stachowiak (1973) is used as a doctrine for system modeling. The theoretical foundation of this project is based on the *Stuttgart business enterprise model* (Westkämper et al. 2009b), as well as on the research work on changeability in factory planning by Hernández (2003) and H-P. Wiendahl et al. (2014, pp. 117–150).

[17] The understanding of business companies as socio-technical systems traces back to labor psychology and follows the belief that an optimization of the technical system, without consideration of the social system, leads to inefficiencies. The association of German engineers (VDI) adopted this understanding to the domain of engineering science. (Ulich 1993, pp. 36–37)

[18] *Decision under uncertainty* means that it is not possible to assign probabilities to the outcomes of an act. It is also referred to as *decision under ignorance*. It is demarcated from *decision under certainty*, with a given outcome, and *decision under risk*, where probabilities can be assigned to all of each act's outcomes. (Resnik 2008, pp. 13–14)

[19] P. Ulrich et al. (1976a, p. 309) predicted, that a synthesis of the system theory with the decision theory is necessary to reach a scientific paradigm's power and precision to solve problems.

1.4.1.2 Rationale context

The rationale context addresses the problem of how theories, hypotheses, and explanations can be proven true (P. Ulrich et al. 1976b, p. 345; H. Ulrich 1984, p. 173). Popper's critical rationalism (Popper 2005) sets a basis with the requirement for falsifiable hypotheses. P. Ulrich et al. (1976a, p. 306) builds on the *criteria of truth* to allow for generalization from empirical observations, which means that inductively drawn conclusions can be justified if a consistency with reality is given. This, in turn, relates to Kubicek's heuristic frame of reference (Kubicek 1977): A verification in the sense of criteria of truth is an empirical review of the discovery context which depends on the researchers presupposition (P. Ulrich et al. 1976a, p. 306).

For the disciplines of applied science the rationale context is of lower importance: Reality is not so much the actual research object but rather an initial point from which possible future states of reality originate, shaped by constructive research activities (H. Ulrich 1984, p. 174). An exhaustive consistency check against an existent reality is, thus, not necessary. But there must be a high plausibility for those theories, hypotheses, and explanations of the applied research in order to built a future reality. J. Müller (1990, p.8-9) consequently replaces the criterion of truth with what he calls the *assumption of truth*. He argues that the results of applied research can never be verified as such, as they don't exist before being realized, and their complexity is generally too high to prove true or false in a sophisticated manner. He differentiates the results of applied research into *conceptual design* and *detailed design*, with the conceptual design anticipating what shall become reality after implementing the technological, detailed design. To prove the assumption of truth the conceptual design must be examined for feasibility and the detailed design for realizability[20] (J. Müller 1990, p. 9). For feasibility examination of a conceptual design a production system model must show sufficient credibility that:

- its implementation is possible by an appropriate detailed design;
- its instances are capable to fulfill all functional requirements;
- it is acceptable and useful for a production system designer.

A detailed design of a production system must be tested to meet the following requirements:

- a system operation under design-use-case-specific circumstances seems possible;
- the sequence of system operations can be fulfilled functionally;
- general production system requirements can be satisfied.

The realizability of models implies the correctness of the model (VDI 3633-1, p. 37), feasible at valid regulations, specifications (PMI 2008, p. 452), and the current state of

[20] The German original uses the expressions "Erfüllbarkeit eines konstruktiven Entwurfs" (feasibility of a conceptual design) and "Realisierbarkeit eines technologischen Entwurfs" (realizability of a detailed design).

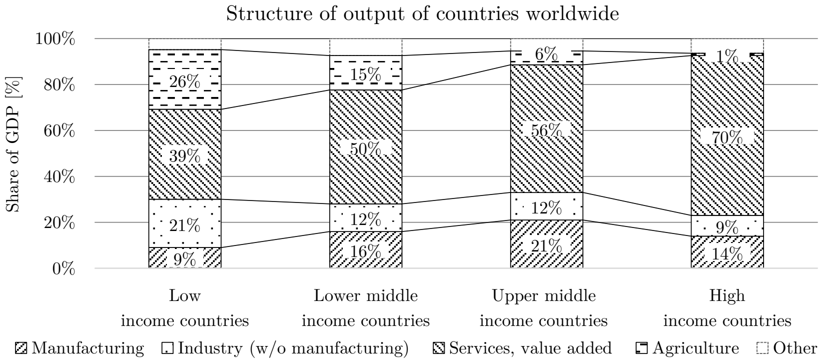


Figure 1.4: Manufacturing % of GDP of countries worldwide (World Bank 2021b)

the art of production. Functional requirements on a production system are deduced from the process requirements of to-be-produced products. Inductive reasoning may be used to verify both the fulfillment of general and functional requirements.

While the conceptual design of a production system can be tested directly, the suitability of the detailed production system design can only be validated on a problem-specific basis (VDI 3633-1, pp. 37–38). It must be ensured that the design reflects the behavior of a subsequently implemented system with sufficient accuracy and meets the requirements of the design (PMI 2008, p. 452). J. Müller (1990, p.9, 11) argues that implementation is possible, when it is probable that the designed system is controllable.

The realizability is proven by means of empiric inductive reasoning. A production system design at a first-tier manufacturer of servomotors serves as the validation project. Operability of the system and fulfillment of required operation sequences are validated by applying discrete event material flow simulation. Possible future states are represented by general requirements and constraints and judged by the fulfillment of defined key performance indicators. General requirements are matched with the general objectives of personalized production systems (Section 1.1).

1.4.1.3 Usage context

While discovery and rational context focus on the rigor of science, the usage context is intended to ensure the relevance of the research subject (Schuh et al. 2013, p. 35; Stokes 1997, p. 81). In design science research, *utility for practice* is established as a clear and common measure of relevance (Winter et al. 2010, p. 269).

This project seeks to enable production systems to be competitive in a volatile world through a tailored design for personalized production. The utility is obvious: A competitive production sector is an engine for growth and innovation, which is of vital importance to a nations prosperity (WEF 2018, p. 1). An analysis by the World Bank (2021b) shows a positive correlation between a country's income and an increase in a country's share of manufacturing-generated GDP[21] (Figure 1.4). Manufacturing accounts worldwide for 16% of GDP (World Bank 2021b). In 2017, 22,3% of the German labor force[22] worked in the sector (Destatis 2019)[23]. It is estimated that every manufacturing job dedicated to create value for final demand generates 3.4 non-manufacturing jobs (MAPI 2016, p. 9). All in all, with their relevance on the GDP and number of jobs, competitive production systems show a high utility to enable a society to prosper.

1.4.2 Research process and outline of the dissertation

The introduction and scope of this dissertation recognized and typified relevant praxis problems in the preceding parts of this Chapter 1. The outline of this dissertation further follows the research process of H. Ulrich (Figure 1.5).

Chapter 2 and 3 clarify terminology and describe the state of the art of relevant factual sciences (terminological-descriptive). Chapter 2 is dedicated to a system theoretical exploration of production systems and details the usage context of this research work. It introduces the paradigm of personalized production including enabling technologies and elaborates on the effects of personalization on production systems. Section 3.1 defines changeability, flexibility and reconfigurability before it discusses existing methods of production system design. Section 3.2 concentrates on the measurement of production system productivity. Section 3.3, finally, carves out the gap in the state of the art.

Chapter 4 to Chapter 6 are a step-by-step development of the methodical design system.

The foundation is the definition of its elements in Section 4.1 and the selection of a suitable system modeling notations and a formal design method in Section 4.2. Section 4.3 introduces the general setup of the methodical design system.

Chapter 5 introduces the generic reference model of a personalized production system. The reference model is created to serve as a template for matrix production system design. The modeling was influenced and recurrently checked against by multiple production system optimization and design projects (analytic-deductive). It is discussed and verified in Section 5.2.

[21]The effect is visible from low- to upper-middle income countries. The manufacturing share of GDP drops again when going from upper-middle to high income with the increase of the service sector.

[22]The share of the labor force was calculated by division of number of people in manufacturing in Germany, with number of Germans actively participating in the labor market (Destatis 2019, pp. 524, 358).

[23]Seen in relation to their GVA account of 25.7% (Destatis 2019, p. 331) they add above average to the value-add in comparison to other economic sectors.

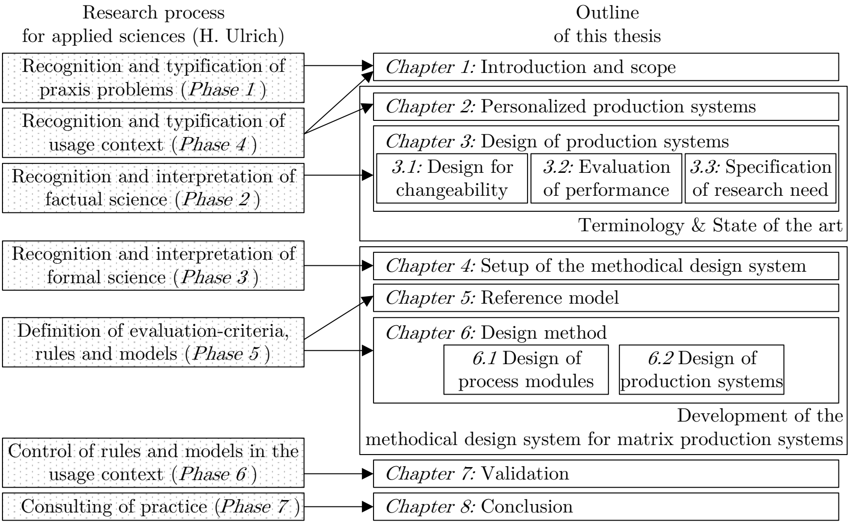


Figure 1.5: Phases of applied research and outline of this dissertation

Chapter 6 develops the actual design method. It consists of two modules: Section 6.1 explains the process module design, resulting into functionally pre-instanced process modules to be instanced by an actual matrix production system design project. The section gives directions on how to compare and select suitable design solutions and how to adapt the generic reference model to use-case-specific requirements (empiric-inductive). Section 6.2 develops the actual matrix production system design method, which instantiates functionally pre-instanced process modules into an overall personalized production system. The chapter delivers guidelines for designing the system and ways to evaluate different design embodiments. To ensure a systematic design process allowing for reproducible results as a prerequisite for the validation, the selection and suitability judgment is built on the formal design method of Axiomatic Design (AD).

Chapter 7 validates the methodical design system. Section 7.1 presents the initial situation at the validation partner, a manufacturer of industrial servomotors. The discussion of results is split into two following sections. In a use-case-centered approach, Section 7.2 implements the methodical design system for the design of the validation partner's production system. The resulting matrix production system design embodiment achieved the initially defined goals of a personalized production system. Section 7.3, then, reflects on the design process with respect to overall requirements of the design method.

Chapter 8 concludes the dissertation and delineates further research possibilities.

2 Personalized production systems

The following chapter explores the usage context of this research work in detail. It defines production in a system-theoretical context, explains origins and characteristics of personalization and discusses the impact of personalization on production systems. Finally, the research question is concretized.

2.1 Production systems for mechatronic modules

2.1.1 Production processes and technologies

Production is defined as the combination of all functions and activities related to the manufacture of goods (Eversheim 1996, p. 3). Production changes shape or material properties (Kahle 1996, p. 4), or assembles subsystems into a product of greater complexity (Warnecke et al. 1974, p. 1) through the input of production factors (VDI 5200-1, p. 3). In a narrow technical sense, this transformation implies the direct product-generating actions of value-adding and material flow (R. Frisch 2010, p. 3)[24]. The thesis understands production as defined by this narrow technical sense[25].

A purposeful, logical, and chronological sequencing of activities creates a process. The output of one activity becomes the input of subsequent activities. An assignment of a resource to an activity results in what is called a transformation, and information supports and controls activities. (Ljungberg 2002, pp. 258–259; A. Kuhn 2008, p. 221)

Transferred into the above-defined context of production, sequences of activities build manufacturing, assembly or material flow processes in order to realize a product (Figure 2.1). Production factors are represented by the production resources.

[24]Cited after Kahle (1996, p. 4).

[25]There exist broader organizational definitions of manufacturing, which factor into the definition of production all indirect measures of order processing and production preparation (Nußbaum 2011, cited after Schuh et al. 2013, p.16; T. Heinen et al. 2008, p. 20; Schenk et al. 2014, p.49), all organizational (specifically lean method toolboxes) and business processes of an enterprise with relevance to manufacturing (Feggeler et al. 2004; Schenk et al. 2014, p. 49), as well as all technical and organizational measures concerning a product during its complete life cycle, from R&D to recycling (Westkämper 2006a, p. 24). According to these definitions, a method to design a production system is part of production. Furthermore, Fandel (2005, p. 2) doesn't limit production to the fabrication of physical goods but includes the creation of immaterial services into the definition. In all these definitions, the narrower, technical understanding of production is differentiated by the term "manufacturing".

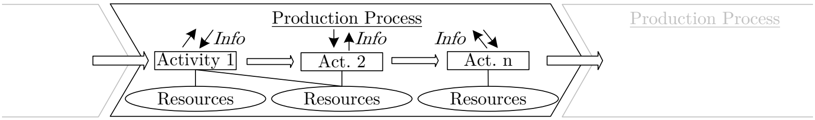


Figure 2.1: Definition of production processes as combination of activities, adapted from (Ljungberg 2002, pp. 258–261; Voigt 2008, p. 24)

DIN 8580 (p. 7) classifies manufacturing processes by six technology main groups (Figure 2.2). Processes are separated according to their purpose whether to change shape or material properties. The type of cohesion of parts or material is used as a further classification criterion within the group of shape-changing technologies.

Assembly is assigned to the fourth main group[26]. An assembly process contains value-adding assembly activities but also handling, control, adjustment, and support activities (Lotter 2012a, p. 2). Support activities are subsumed under selected manufacturing processes of other main groups, such as deburring, printing, and cleaning.

According to DIN 8580, value-adding assembly processes are manufacturing processes. To establish clear disctinctions, this thesis will use two terms in the following chapters:

- assembly process, for main group 4 manufacturing processes
- manufacturing process, for all other main group processes

An easy differentiation is possible by using the number of processed parts: Manufacturing processes change the properties of only one part at a time. Assembly processes build (sub)assemblies of a final good with more than one part. The aggregate state of assembled parts may be solid or non-solid (Warnecke et al. 1974, p. 1).

2.1.2 Mechatronic machine modules

The objective of this thesis defines machine modules as the product scope. Product modules are subsystems of a product with modular architecture (Göpfert 2009, p. 33). The product architecture is the scheme by which product functions are allocated to physical components. It consists of the function structure, the mapping from functional to physical structure and specified interfaces among interacting physical components (K. Ulrich 1995, p. 2). Modules are, thus, relatively independent units with separable interfaces (Göpfert et al. 2013, p. 279; Göpfert 2009, p. 116; VDI 2222-1, p. 10)[27,28]. They carry the functions

[26] In the German original of, the term *Fügen* refers to value-adding assembly technology. The literal translation of assembly is *Montage*. *Montage* refers to the overall process, including value-adding, auxiliary, and support activities, as defined by Lotter (2012a).

[27] An integrated product architecture, on the contrary, is built with strong interrelations and dependencies between subsystems, so that they can not be separated physically (Göpfert 2009, p. 34)

[28] Appelfeller et al. (2011, p. 124) names a complete engine, the seat system of a car, including base structure and the steering system, as examples of product modules in the automotive industry.

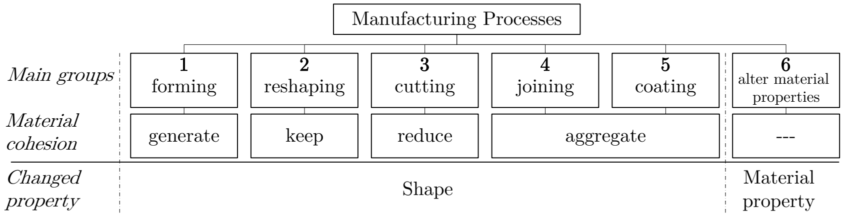


Figure 2.2: Classification of manufacturing processes (DIN 8580, p. 7)

of a product (Feldhusen et al. 2008, p. 39). Physically, a module is an aggregation of parts and components. The independence of modules doesn't necessarily make them independently marketable (Feldhusen et al. 2008, p. 38), but they must be designed as complete and ready-to-install units of a final assembly (Arnold 1997, p. 101).

The modular product architecture enables an organizational division of production labor across the supply chain. A product module is allocated to the first tier of the supplier pyramid[29] (Figure 2.3). The assignment of module production on the first supply level, delivering to final assembly, is also valid when production is done in-house at the OEM.

Mechatronics is an interdisciplinary field of engineering science that combines mechanical engineering, electrical engineering and computer science. Mechatronic systems have a basic mechanical structure that is combined with non-mechanical components, sensors, actuators and processors to form a functional unit (Czichos 2006, p. 1). Mechatronic machine modules are finished goods of discrete manufacturing[30]. Discrete manufacturing produces countable piece goods with a defined form (Bakir et al. 2013, p. 18; Brede 2005, p. 137). Mersch et al. (2011, pp. 9–10) characterizes discrete manufacturing as follows[31]:

- a heterogeneous process sequence, required for different product variants
- a partly flexible process sequence per variant[32]
- production resources, which are often equipped for a range of product properties
- manufacturing and assembly processes clearly separated from transportation
- no change of product properties during transport
- transport flexibility of routing, transport lot size, and sequence of product variants
- the possibility to share transport equipment among different variants

[29] The difference between system and module sourcing (at first-tier level) lies in the degree of integration of the supplier into the product creation process of the OEM: A system supplier is responsible for R&D. A module supplier only carries out the physical assembly of components (Andreßen 2006, p. 21). This does not make any difference for the product architecture and the assembly process of the module. Hence, machine module and machine system are used synonymously in this thesis.

[30] In contrast to process engineering which produces formless goods (gas, liquids, bulk materials).

[31] Listed characteristics are a selection by relevance to the design of a production system's organization structure. For the complete list of characteristics refer to Mersch et al. (2011, p. 10).

[32] Full flexibility is restricted by product architecture, workpiece shape, and technological process couplings.

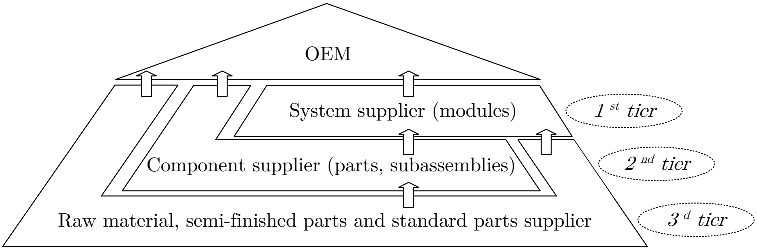


Figure 2.3: Supplier pyramid by value-add level (Wildemann 2018, pp. 94, 96)

Typical industries that execute discrete manufacturing of machine modules are the machine building industry and the automotive industry.

2.1.3 System theoretical classification

A production system is a socio-technical system (Westkämper 2009, p. 4; T. Heinen et al. 2008, p. 20), designed to realize production. Modern system definitions originate from the general system theory of Ludwig von Bertalanffy (Ropohl 2009, p. 72). Von Bertalanffy sought for a model to explain that the constitutive characteristics of a unified whole are more than the sum of its isolated parts. His understanding of systems is that of elements in mutual interaction (von Bertalanffy 1969, pp. 45, 55). On each element a set of properties (and thus functions) of these elements is defined. Accordingly, a system is a set of its elements E, functions F, and relations B between the elements: $S = \{E, F, B\}$ (Patzak 1982, p. 53).

From this system definition, Ropohl (2009, pp. 75–76) derives the *functional*, *hierarchical*, and *structural concept* to model a system in all its aspects (Figure 2.4). The functional concept describes the system as a black box which is represented by the "transfer relation" of inputs to outputs to realize the overall function of a system (Patzak 1982, p. 57). The structural concept defines the dynamic architecture of the system via the system's internal network of possible relations. Different system behaviors arise from executed "coupling relations" (Patzak 1982, p. 57). The hierarchical concept, finally, describes the static system architecture via different system levels. The system is built of subsystems and is separated from its supersystem or surrounding environment by its system boundary.

Tailored for technical systems, Ropohl's system concepts are a suitable model for the system theoretical positioning of production. Respectively, the design of a personalized production system needs to consider all three system concepts: The overall functions must be derived. Production system elements have to be determined by number, function,

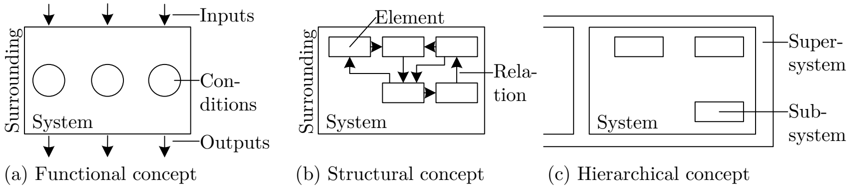


Figure 2.4: System theory concepts (Ropohl 2009, p. 76)

and inner architecture. The relations between these elements need to be defined. And finally, the hierarchy of the personalized production system and its embedding within supersystems and environment needs to be specified.

The overall function of any production system must correlate with the above-specified production objective to realize production processes. For the case of this thesis, it may be stated as: Produce products while fulfilling the objectives of personalized production.

The production system is a subsystem in the hierarchy of the manufacturing enterprise and thus part of a production network, a factory and a production segment[33]. It is conventionally broken down into production cells and workstations[34]. As this thesis follows the definition of production as value-adding processes and associated logistics activities[35], the system's inner structure is build up by the value-adding subsystems of manufacturing and assembly as well as the logistical subsystems for the physical material transport.

From the given definition of production, it also follows that the technical aspects of the socio-technical system dominate[36]: The inner structure of the production system is build by machines and technical equipment (Schmigalla 1995, p. 83). Humans act as operators of the technical processes (Hubka 1984, p. 31). Manufacturing and assembly process chains are formed through multiple, successive relations of these production system elements (Schmigalla 1995, p. 81; Eversheim 1996, pp. 112, 133).

There is an inseparable dependency between product architecture and process structure. The chronological sequence of a production process is build according to the degree of freedom given by the product architecture: Production processes are either required to be executed after each other or can be executed independently (Ammer et al. 1986, p. 94).

[33]An overview of different definitions of production system hierarchies is given in Tables B.1 and B.2 (Appendix B).
[34]Some authors add processes at the lowest level, as a subsystem of the workstation.
[35]Compare section 2.1.1 for the definition and differentiation from a broader organizational understanding.
[36]Seen from a process perspective, human operators are production resources. Gutenberg (1989, pp. 67–68) further introduced the dispositional factor to the classical production factors to embrace the human labor concerned with (managerial) decision problems, such as goal setting, design, organization, planning and control (Schüler 2000, p. 43). The human role as disposition factor can be neglected when designing the organizational structure of a production system (Fandel 2005, p. 2).

If the elements of the production system are connected in a series, they correspond to the stations of a line. In the case of a possible flexible routing among them, a relationship between individual elements only arises when required by the transport of a production object. Complex material flow relationships with reflows are then possible.

Flexibly linked process modules are introduced as a solution element to realize flexible routing (Figure 1.2). Process modules are cyber-physical fractals of the production system (Bauernhansl 2014b, p. 21). They are independently operable, feature a plug-and-work character, and can be multiplied, displaced, reconfigured, or eliminated as a whole (Aurich et al. 2003, p. 216; Roßkopf et al. 2004, p. 238). Process modules perform defined production (sub)processes (Bauernhansl 2014b, p. 21; Bauernhansl 2014a, p. 275; Krebs et al. 2011, p. 915; Nyhuis et al. 2008b, p. 219; Reinisch 2008, p. 106; Roßkopf et al. 2004, p. 238; Aurich et al. 2003, pp. 216–217; Suh 1999, p. 125). A process module contains a variety of resources needed to ensure its functionality as an autonomous unit of the production system. It is divided into value-add, support, and connecting (to material flow) subsystems (Baudzus et al. 2012, p. 345; Baudzus et al. 2013, p. 1; Feldmann et al. 2004, p. 186). The functional scope of a process module depends on the complexity of the production program and the functional segmentation of the production system elements (Bauernhansl 2014b, p. 21). They can, however, be coupled in a network of modules, thus creating an unit of higher functional integration (Lotter et al. 2009, pp. 134–135; Konold et al. 2009, p. 110; Nyhuis et al. 2008b, p. 219). Process modules belong to the production system level of machine and work station.

The system theory differentiates four system types according to the diversity and the dynamics of the system elements (Figure 2.5): A trivial system transfers one specific input, always with the same transformational function, in a predictable way into one specific output. It is neither dynamic nor numerous in its elements. A system becomes complicated with an increasing number and variety of elements. If the interrelation of elements in a complicated system is static, the system can be described explicitly, provided that sufficient effort is invested. A behavior analysis of a complicated system is possible using statistical methods. In a complex system, the relations among elements are not static but change dynamically. The difference between a dynamic complicated system and an actual complex system lies in the structural concept. A dynamic complicated system is built of homogeneous elements, and there is a relatively low intensity of element interrelation. (Bandte 2007, p. 94; Haberfellner et al. 2015, pp. 38–39; H. Ulrich et al. 1995, pp. 58–59)

The dynamics of a system are driven by its external requirements which force a system to change. Complexity is never absolute but a relative measure of uncertainty in achieving

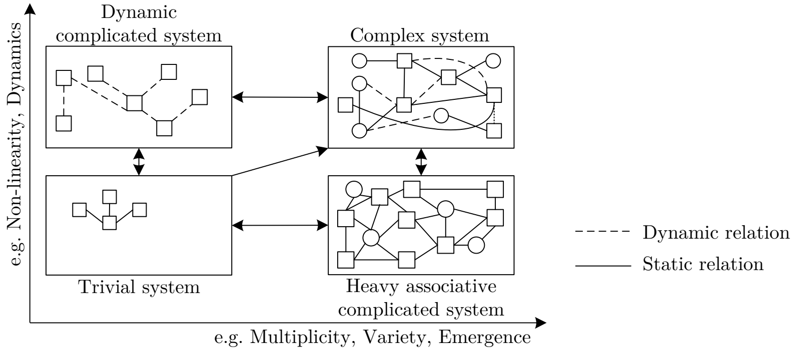


Figure 2.5: System complexity typification (Bandte 2007, p. 93; H. Ulrich et al. 1995, p. 61)

specified requirements[37] (Suh 2005, p. 55). Time-dependent complexity is conditioned by an unpredictable combination of future events[38] (Suh 2005, pp. 10–11). In a dynamic environment, a system requires internal complexity to meet external complexity sufficiently[39] (H. Ulrich et al. 1995, p. 65; Jäger et al. 2014, p. 646). Hence, it is impossible to eliminate complexity altogether within a turbulent ecosystem. It is, however, possible to achieve a dynamic complicated system instead of a complex system by design.

Production systems are usually non-trivial systems[40]. Rigidly linked stations in a production line form a complicated system. The line doesn't show enough internal complexity to serve the (product and volume) variety of customer demand[41]. A production system of flexibly linked process modules is a dynamic system. To achieve dynamic complicated instead of complex systems, a design needs to aspire towards low system heterogeneity[42]:

- by a small number of process modules of homogeneous functional scope, and
- by high functional integration of process modules, to reduce transport relations.

[37] Complexity may also be triggered by a lack of system understanding. *Imaginary complexity* makes the system complex for the user, even if the system does not show *real complexity* per se. (Suh 2005, p. 10)
[38] Time-dependent *combinatorial complexity* turns into *periodic complexity* by periodic system re-initialization, thus limiting the number of probable combinations (Suh 2005, p. 72).
[39] If the dynamics of the system match the dynamics of external factors, there is no uncertainty about achieving requirements. The design is then not complex but suitable (Suh 1999, p. 118).
[40] Examples of complexity in manufacturing systems are given by Suh (1999, p. 125) and Abdelkafi (2008).
[41] Sections 1.1 and 1.2 explain the insufficiency of the production line for turbulent business environments.
[42] Low heterogeneity follows a small *absolute* number of elements and a small number of *different* elements.

2.1.4 Prevalent types of production systems

Production systems are commonly described by two different system views: organizational structure and process structure[43]. The former addresses a system's static architecture; the latter subsumes the order of the system's business processes (Frese 2014, p. 3.1; Wöhe et al. 2000, p. 175). Both views incorporate functions, elements, relations, and the hierarchical setup of the system, i.e. all of Ropohl's system theory concepts (Section 2.1.3).

2.1.4.1 Organizational structure

Organizational structures of production systems are typified by the chronological, spatial, and technical interaction of production factors (i.e. workers, operating resources, materials of processed goods) (Petersen 2005, p. 51)[44]. The functional scope (technical typification criterium) and the movement (chronological-spacial typification criterium) of the system elements determine the type[45]. Petersen (2005, p. 52) further differentiates the kinematics of elements into movement *during a process* and movement *between process steps*.

The five classical production organization structures can be ordered in a scheme by these typification criteria (Figure 2.6).

- In a job shop fabrication (1), production resources are grouped according to their manufacturing process technologies. Processed goods move between job shops, if a subsequent process step needs a different technology. Job shop production usually works in batches (Wildemann 1998, p. 85).
- In a workbench fabrication (2), the worker is the defining typification criteria[46]. The worker moves from workbench to workbench between process steps.
- Building-site production (3) is applied if the produced goods are too big to be relocated during manufacturing. Workers and production resources are moved to the points of usage[47].

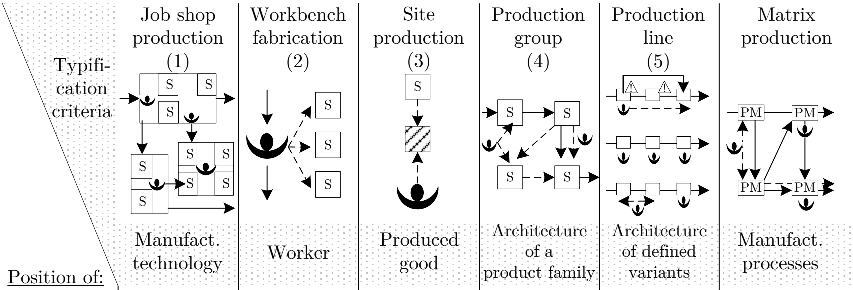
[43] German: *Aufbauorganisation* (organizational structure) and *Ablauforganisation* (process structure). Various authors refer to organizational structure (Frese 2014, p. 3.1; Hesse 2012, p. 196; Voigt 2008, p. 227; Siegel 2008, p. 11) with the alternative terms of organizational type (Eversheim 1996, p. 135; Corsten et al. 2012, p. 31; Küpper et al. 1995, p. 18), manufacturing structure (Grundig 2013, p. 153), manufacturing principle (H-P. Wiendahl et al. 2014, p. 276; Bertsch et al. 2013, p. 121), basic assembly structure (Konold et al. 2009, p. 45), structure type (Schmigalla 1995, p. 117), operation system (Wöhe et al. 2000, p. 190), or organizational arrangement type (Küpper et al. 1995, p. 18; Eversheim 1996, p. 111). Instead of process structure (Frese 2014, p. 3.1; Wöhe et al. 2000, p. 190), process type is used by Schenk et al. (2014, p. 371) and Heiderich et al. (1998, p. 88).

[44] Corsten et al. (2012, p. 29) give a comprehensive overview of typification criteria for production.

[45] The organizational structure is closely related to the structural and the functional concept of a system. The relations of the structural concept define possible movements in the system. The functional scope reflects the transfer relation from input to system output.

[46] Workbench fabrication is rarely used for industrial production, apart from prototyping or in indirect support areas, such as toolmaking (H-P. Wiendahl et al. 2014, p. 278).

[47] Building-site production has no relevance to this thesis with its scope of application on machine modules.



Position of:	Job shop production (1)	Workbench fabrication (2)	Site production (3)	Production group (4)	Production line (5)	Matrix production
Workers	Fixed	Moving	Moving	Moving	Fixed / Moving(flowline)	Fixed or Moving
Operative resources	Fixed	Fixed	Moving	Fixed	Fixed / Moving(flowline)	Fixed
Processed goods	Moving	Moving	Fixed	Moving	Moving	Moving

Worker; Processed good; S Station; PM Process module; Worker pathways; Flow of processed goods

Figure 2.6: Classical production organizational structures (Schönsleben (2016, pp. 209–212); H-P. Wiendahl et al. (2014, p. 277); Wöhe et al. (2000, pp. 440–442); Schimke et al. (1977); Spur (1986) cited from Spath et al. (2014, p. 10.28); Eversheim (1996, p. 105), enhanced by matrix production)

- A production group (4) contains all processes needed to produce all the variants of a defined product family. The material flow between production resources is flexible. Material and workers move in between process steps. Production groups often produce in batches.
- A production line (5) arranges manufacturing processes according to the SOO of defined variants. Processed materials flow unidirectionally over the stations of the line, generally as "one piece at a time" production. There are three types of production lines[48]: In sequentially arranged stations with buffers between them skipping of stations is possible. Cycled line and continuous flowline are clocked production systems with coupled stations. Stations cannot be skipped, as the work content per stations is synchronized. The continuous flow line is the only classical production structure in which the worker moves during the process together with the processed good. In the systems of sequentially arranged stations and cycled lines, processed goods are stationary during operation and move in between process steps.

This thesis promotes a matrix production of flexibly linked process modules as a layout paradigm for personalized production systems. The organizational structure of flexibly linked process modules is characterized by stationary operative resources, linked by a

[48] In German, they are clearly differentiated terminologically by the terms *Reihenfertigung* (sequentially arranged assembly stations), *Taktstraße* (cycled assembly line) and *Fließfertigung* (continuous flowline).

one-piece material flow. In contrast to line production, the flow is flexible between the process modules. This allows for a varying technological sequence, as in a job shop or group production. The typification criteria is the manufacturing process. Processed goods are stationary during operation and move to another process module if no more process steps can be performed on the current module. Workers may be allocated one-to-one to a process module or move from one process modules to another in between operations for higher worker utilization.

A conceptual combination of the classical organizational structures with automated operating resources is referred to as “modern types of production organizational structure” (Petersen 2005, pp. 198–218; Nebl 2011, p. 382). Established modern types with distinct names are Computerized Numerical Control (CNC), general purpose numerically controlled machining center (BAZ), Flexible Manufacturing System (FMS), Reconfigurable Multi Technology Machine (RMM) as well as cycled line and continuous flow line.

The typification by organizational structure is closely related to a production system’s output of similar products[49]. Eversheim (1996, pp. 103–105), Wöhe et al. (2000, p. 440) and We. Kern (1996, p. 1640) accordingly define the following production types:

- single unit, make to order production (one piece)
- serial production of relatively homogeneous goods (series)
- batch production for similar variants, processed on the same equipment (batches)
- customer order-neutral, make to stock mass production of standardized products (mass quantities)

When plotted over the repetition frequency of a variant[50], it is possible to assign these organizational structure types to the categories of output (Figure 2.7). Personalized production lies outside of the trend line: High product variety, i.e. small repetition frequency, needs to be produced in large numbers.

From the assignment of typical organizational structures types to the output of production, it can be concluded that an organizational structure needs to follow the product life cycle for efficient production. A product life cycle models the development of the annual sales volume in the four phases: introduction, growth, maturity (or stabilization), and decline (Malakooti 2014, pp. 26–27)[51]. In a common adaptation, a workbench fabrication for prototyping is followed by a serial or mass production line system before going back to a

[49]Eversheim (1996, p. 103) points out that categories of produced goods overlap and are strongly dependent on the industrial sector: The mass quantity for one sector may be a small series volume for another sector.

[50]The repetition frequency is measured as the number of lots of a specific part number per time period.

[51]Extended life cycle models from cradle to grave include inception, engineering design, market introduction, production phase-out, and spare parts service as additional phases before or after the manufacturing phases (H-P. Wiendahl et al. 2020, p. 102). Marketing activities and re-engineering (e.g. facelift) alter the idealized curve of the life cycle (Benkenstein et al. 2009, p. 54).

decoupled, less productive, single-unit production system to cover the decline in production need (Feldmann et al. 2001, p. 486). Nevertheless, the limitation of a production system to a certain range of volume causes opportunity costs due to lost sales if the system is dimensioned to a smaller volume than required, or causes waste of occupied space and underutilized equipment if the system is dimensioned too large (Vollrath 2002, p. 94; Reinhart et al. 1999b, p. 414; Reinhart et al. 1998, p. 56).

In operational practice, the classical organizational structures are sometimes modified to hybrid forms to, for example, increase utilization of resources or reduce transport (Rath 1989)[52].

2.1.4.2 Process structure

A process structure has the mandate to harmonize processes in terms of time, space, and scope (Frese 2014, p. 3.2). In a production system, the harmonization of operating processes is the task of production control, which is responsible for *order creation*, *order release*, *capacity control* and *order sequence planning* (Lödding 2008, p. 7).

Order creation determines a planned input. Order release determines the point in time at which an order is triggered into a production system. Capacity control defines working times and allocates workers to the production system elements. The order sequence sets priorities for the processing of orders, which is relevant when different orders compete for joint resources. Order sequence planning is a resource-oriented process, that sorts the orders in a waiting queue in front of a station or a machine. (Lödding 2008, pp. 10–14, 320–321)

An organizational structure of flexibly linked process modules may contain several process modules of similar functions, and it gives the flexibility to process a product with alternative operation sequences, following the degree of freedom provided by the product architecture. Thus, it is necessary to add two additional tasks - *order distribution* and *operation sequence planning* - to the responsibilities of production control (Fries et al. 2020, p. 34). Order distribution assigns the manufacturing processes of certain orders to certain process modules. Operation sequence planning determines the order of the manufacturing processes of one product.

Order creation is, essentially, a planning activity. In personalized production, any planned order directly correlates to a customer order.

Order release concepts are correlated to classical organizational structures and the volume output categories of production (Figure 2.8): The concept of cummulative quantity (FSZ) compares target to actual production quantities at timed instants. It is tailored for mass production on production lines. Kanban and ConWIP are consumption-controlled

[52] Cited by Nebl (2011, pp. 370+).

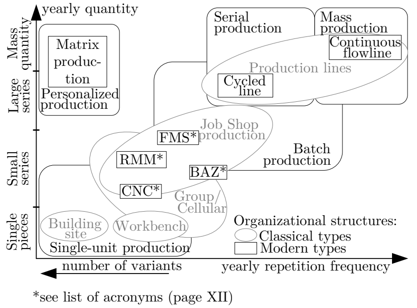


Figure 2.7: Organizational structures related to volume and variety (Eversheim (1996, pp. 103–105), Wöhe et al. (2000, p. 440), Spath et al. (2014, p. 10.10), Siegel (2008, p. 14), Nebl (2011, p. 382) and We. Kern (1996, p. 1640), enhanced by personalized production)

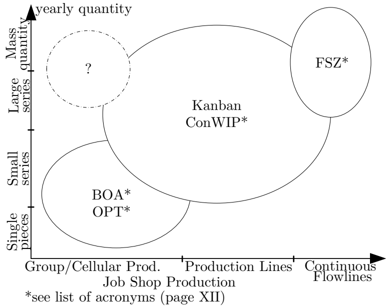


Figure 2.8: Production control concepts related to output volume (H-P. Wiendahl et al. (2020, p. 341), H-P. Wiendahl (2010, p. 330), Luczak et al. (1998, p. 64), H-P. Wiendahl (1992, pp. 15+), and Eversheim (1996, pp. 159+))

procedures which release orders against a target stock. Orders are triggered when the inventory level inside of the supermarket[53] (Kanban) or within the complete system (ConWIP) falls below a refill control limit. Both procedures are built as self-steering loops to control production lines, groups, or job shops. Kanban and ConWIP require large capacity flexibility. Optimized-Production-Technology (OPT) and the Utilization-oriented order release concept (BOA) are order release concepts of group and job shop production. OPT algorithms pursue a high utilization of a stable bottleneck. BOA assumes alternating bottlenecks and optimizes the general system utilization. Priorities are set with respect to the urgency of orders and a defined permissible backlog per station.[54] (H-P. Wiendahl et al. 2020, p. 341; Schenk et al. 2014, pp. 398–404)

Job shop and group production control concepts share the characteristic of flexible routing with the organizational structure of flexibly linked process modules. They are, however, not tailored for the high-output quantities of personalized production. The motivation to respond more flexibly[55] to disruptions and change has led to the development of new production control concepts. Examples include the "3-liter-PPS" concept (Färber et al. 2002), the concept of opportunistic coordination (Gössinger 2000), and the autonomous

[53]A supermarket is an inventory within a Kanban-controlled system, that decouples successive processes. It has a defined min and max level of inventory, and it works with the FIFO and the pull principle. (Ohno 2013, p. 62)

[54]For further details on the classical concepts, see e.g.: Lödding (2008), Schönsleben (2016), Corsten et al. (2012, pp. 602–610), and H-P. Wiendahl et al. (2020, pp. 340–351).

[55]Examples are rerouting, late commitment, and decentralized, autonomous control loops.

product-manufacturing cycle (Windt et al. 2010; Jeken et al. 2011). None of these new concepts uses all available degrees of freedom that an organizational structure of matrix production provides.

This thesis focuses on the design of a production system's organizational structure. The development of a tailored process structure for a matrix production of flexibly linked process modules is not in the scope of this work. A complete discussion of such modern production control concepts is, therefore, not given here. Capacity control and order sequence planning including the new tasks of order distribution and operation sequence planning influence a personalized production system's organizational structure and must, thus, be considered in the production system design.

2.2 Personalization

2.2.1 Individualized products

Personalized production creates highly *individualized products* for individual customers (Bauernhansl 2014b, p. 10). Individualized products are standard products with customer specific parts (Baumberger 2007, p. 26). They have a modular and typically open architecture, which allows for the combination of *common modules*, *customized modules*, and *personalized modules*[56] (Hu 2013, p. 6; Koren 2010, p. 37). Common modules are shared across platforms; customized modules are individually selectable; and personalized modules are created for a specific customer (Hu 2013, p. 6). Personalization is mostly possible in predefined sections of the product architecture. The requirements of personalized modules relate to additional functions, special performance, special interfaces, conditions of operating environment, a specific design, or dimensions (Lindemann et al. 2006, p. 9).

Personalized production works by the pull principle (Figure 2.9): The definition of the general product architecture and the product development of common modules are frontloaded to a design phase prior to sale. The configuration of modules, as well as the development of personalized modules, are part of a personalized design phase after a purchase order, in which the customer becomes a value-adding stakeholder of the product definition[57] (Koren 2010, p. 31). With the transition from product-centered to service-centered business models and the trend of digital servitization, the collaboration with

[56]It follows, that parts and subassemblies on the component level, introduced in the value add level supplier model (Figure 2.3), need to be modules themselves. Section 2.1.2 characterizes modular products.

[57]The customer adds value by configuration of modules and by suppling all necessary information for personalization (Koren 2010, p. 31). In a deviating definition, Fenech et al. (2019, p. 8) opine that customer preferences for individualized products are identified through existing data about that individual. The authors argue that there is no input needed from the customer besides allowing the use of their purchasing or profile data. While this may be the state of the art for marketing and partly

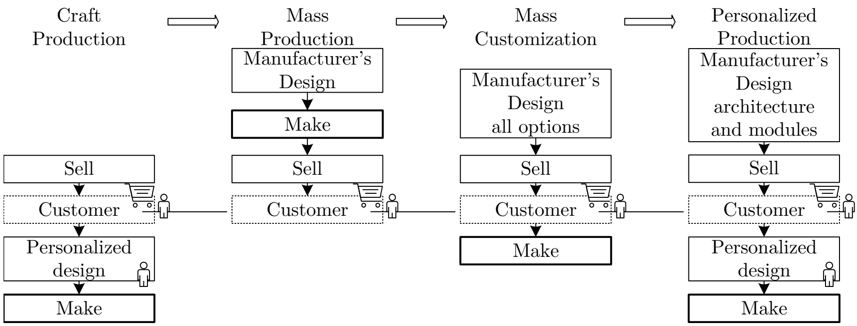


Figure 2.9: The customer role in different production paradigms (Koren 2010, p. 33)

customers, suppliers, and other partners intensifies and influences the individualization process (Favoretto et al. 2022, p. 113). Smart individualized products become platforms for services and individual services are offered to the customers throughout the complete product lifecycle. Hence, the product architecture and common modules are the standard in an individualized product. The customer-specific parts consist of the configuration of modules and the design of personalized modules and components.

Individualized products are clearly differentiated from bespoke, individual products, that are entirely crafted according to the wish or characteristics of a specific customer (Koren 2010, p. 33). There is also a clear differentiation to the modular products of mass production, which are designed with a product family architecture and some customized modules in predefined options of configuration[58] (Hu 2013, p. 5; Koren 2010, pp. 27–35). That means that the product concept of personalized production incorporates the product concept of mass customization (Wehner et al. 2016, p. 144).

2.2.2 Industrie 4.0 enabler technologies

Driven by the development of ICT, Industrie 4.0 (I4.0) represents the trend of a digitally connected production (Figure 2.10). Cyber-physical systems (CPSs) are used to advance automation, to the point of autonomous and self-optimizing production as the highest maturity level of I4.0. (acatech 2017, pp. 10, 16; Steinhoff 2016, p. 1; Monostori et al. 2016)

for consumer goods it is not (yet) the case for mechanic and mechatronic product systems of the machine-building or automotive industry.

[58]In mass production, customization is often postponed and thus limited to final assembly, decoupled from customer-neutral manufacturing by a customer order decoupling point (Piller 2006, pp. 201–203). For a complete introduction into the production paradigm of mass customization refer to Piller (2006). For the selection of suitable organizational structures for mass customization see Siegel (2008, pp. 68–74).

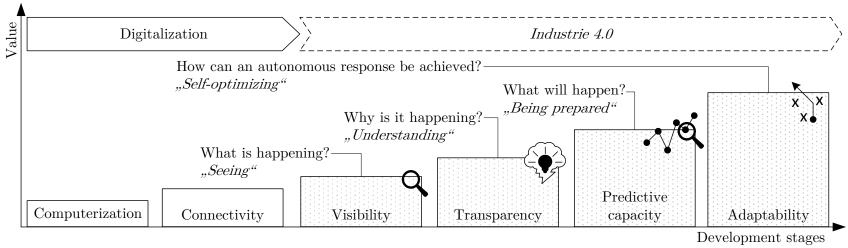


Figure 2.10: Stages in the Industrie 4.0 development path (acatech 2017, p. 16)

I4.0 is associated with a number of enabler technologies[59]:

- Universal hardware: Conventional automation equipment is often tailored to few variants, through the form closure principle applied to the design. Developments in the last decades have achieved numerous alternative examples of universal and self-adaptive manipulators, grippers and jigs (A. Frisch 2020; Manz et al. 2016; E. Brown et al. 2010). The demand for industrial robots and automated guided vehicles (AGVs) in production has increased continually since 2010 (IFR 2020, p. 13), and human-robot collaboration and rapid and intuitive programming are being developed (Naumann et al. 2014).
- One piece production technologies: Die and tool shape-dependent mass production technologies (such as molding and forming) are being evolved for one-piece production. The I4.0 literature particularly highlights additive manufacturing technologies for manufacturing without a mold. New materials and improved processes make them suitable for industrial production. (Heß 2008, p. 19; Klocke et al. 2003, p. 7; Geiger et al. 2016, p. 174)
- Mixed reality technologies: As a communication interface between operators and CPSs, mixed reality technologies are able to provide information (such as variant-specific assembly instructions) in a human-centered way. (Gorecky et al. 2014, p. 233; Bischoff et al. 2015, p. 24)

[59]The listing is an excerpt of the most relevant enabler technologies for the topic of this thesis. For a complete overview about technological and technical enablers of I4.0 refer to Andelfinger et al. (2017), Bauernhansl et al. (2016), Vogel-Heuser et al. (2017), Botthof et al. (2015), Sendler (2016), and Roth (2016).

2.3 Impact of personalized production on production systems and system design

Personalized production follows an integrated cost and differentiation strategy[60]: Individualized products are to be produced with high productivity in high volumes in a pull-type business model (Figure 2.11).

The cost focus on high volumes can only be achieved with industrial production. Economies of scale and scope require shared processes between variants and an intensive common usage of production factors for the production of the different variants. As a consequence, a personalized production system cannot be assigned in a one-to-one relationship to a certain family or generation of product variants. An adaption of the system to new variants, or an elimination of production processes that are no longer required, must be possible during operation through incremental integration or disintegration of production system elements.

To foster the customer focus through the production of individualized products, aiming at a market of one (Koren 2010, p. 15), the production system must be designed to run with lot-size-one processes as a standard business practice[62]. The individual module configuration of individualized products is contradictory to a linear setup of production resources, connected in series. Thus, the production system itself needs to be modular.

The modular system structure, in turn, must allow for a variant-specific configuration of the process sequence with short decision lead time[63]. Finally, the option of personalized components in individualized products leads to a production system that integrates both lot-size-one-capable manufacturing and assembly technologies within one system.

At the start of personalized production system design, actual variants are widely unknown. Product configuration and the design of personalized modules are defined at

[60]Compare Porter (2004, pp. 34+) regarding the generic competitive strategies of *overall cost leadership*, *differentiation* and *focus*. Promoters of mass customization argue that this previous production paradigm already suceeds in refuting Porter's hypothesis of the dichotomy of the two competitive strategies of cost leadership or differentiation[61]. Offering different preconfigured product variants to customers in packages as actually done by mass customization manufacturers still has a focus on targeted market groups (Koren 2010, pp. 28, 32). Essentially, mass customization pursues a hybrid competitive strategy (Piller 2006, p. 181) but achieves only a focus strategy albeit with a wide focus on large markets.

[62]The standard business of serial production (in mass production and mass customization) is a production of established variants. Customer-individual products are treated as exception and managed as a project. (Spath 2009, p. 21)

[63]For general details on decision lead times in production planning compare H-H. Wiendahl (2011, p. 291). Fries et al. (2020, p. 23) explain that personalized production changes the classical distribution of decision tasks between (long-term) factory planning and (short- and medium-term) PPC. While a long-term planning horizon of factory infrastructure persists the medium-term production system design becomes a short-term configuration to match the requirement of production orders ad hoc.

[64]The same illustration format was used by Gräßler (2004, p. 15) to explain mass customization.

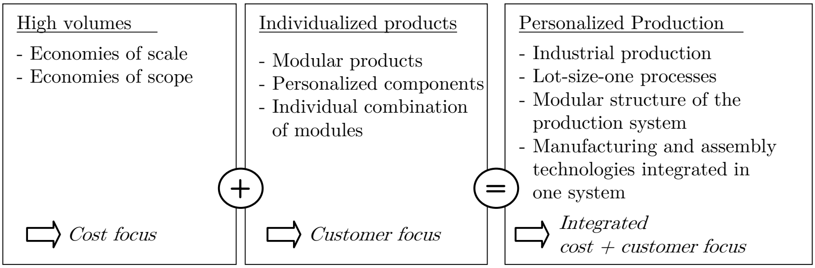


Figure 2.11: Strategy and characteristics of Personalized Production[64]

the time of the customer order. The system needs the functional capabilities to produce products ad hoc that have potentially never been produced before. Production system design thus faces the major challenge of specifying design goals and evaluating design embodiments[65] for a partly unknown and changing production program. Two dimensions are affected by these uncertainties:

1. The precise design goals are unclear.
2. The requirements for evaluation are unclear.

Considering this, the guiding research question of this thesis (section 1.3), *how to design a matrix production system for the requirements of a personalized production*, concretizes the following subquestions:

- *How to set design requirements and consider them during the complete design process?*
- *How to design the system, i.e. functional segmentation of process modules (functions), capacity of modules (elements), layout and process sequence configuration (relations)?*
- *How to evaluate design solutions for functional suitability for different variants?*
- *How to measure the potential performance of design embodiments?*

[65] According to VDI 2221 (pp. 3, 13, 21), each design process must be accompanied by a technical and economical (comparative) evaluation of the design embodiments.

3 Design of changeable production systems: State of the art

This chapter examines the state of the art of changeable production system design in the two dimensions of system design (Section 3.1) and evaluation Section 3.2. To create a common understanding both sections first define relevant terminology.

On the basis of the reviewed state of the art, Section 3.3 justifies the research needs by examining the deficits of existent methods for the design of personalized production systems.

3.1 Design for changeability

3.1.1 Changeability, flexibility, and reconfigurability

Changeability is defined as the ability of a production system to adapt its structure, processes, and behavior rapidly and efficiently. The reactive or anticipative adaptation is triggered by internal or external change drivers. Changeability is intended to keep the system efficient in a turbulent business environment. (Hernández 2003, p. 52; Westkämper et al. 2000, pp. 24–25; Wirth et al. 2000, pp. 459–461; H-P. Wiendahl et al. 2000)

Other than a flexible system, however, a changeable system does not encompass the complete range of possible future system states. A changeable system needs pre-investment only into changeability enablers inherent to the system (Zäh et al. 2005, p. 4; Hernández 2003, p. 52; Westkämper et al. 2000, p. 24; Seebacher 2013, p. 22). This provides the system with the potential to move its current range of capabilities, i.e., its *flexibility corridor*, to a different level of system requirements (Figure 3.1). A *change corridor* (Erlach et al. 2014, p. 126)[66] defines the overall scope of possible flexibility requirements, while the actual position and width of the future flexibility corridors stay unknown[67].

According to H-P. Wiendahl et al. (2014, p. 133), the five primary changeability enablers are: *universality*, *mobility*, *scalability*, *modularity*, and *compatibility*. As modularity

[66]The definition originates from Klemke et al. (2011, p. 925) who used the term *changeability corridor*.

[67]Some authors advocate the differing view that changeability is a system characteristic without predefined limits, e.g. Berkholz (2008, p. 14). In the logic of these authors a change corridor does not exist.

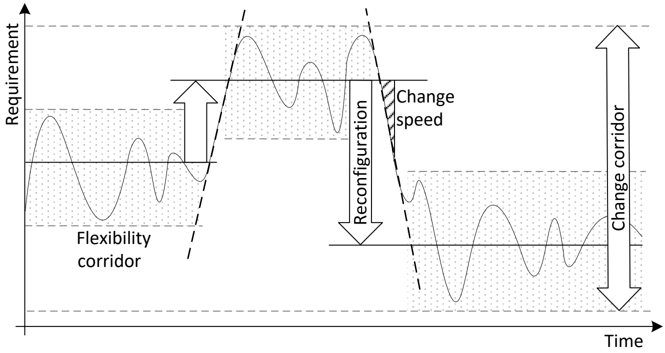


Figure 3.1: Flexibility and changeability corridors (graphical) (Zäh et al. 2005, p. 4)

intensifies all other enablers, it is seen as a fundamental property of a changeable production system (Erlach 2020, pp. 303+, 316+; Denkena et al. 2005, p. 73).

Changeability uses a system's flexibility to avoid a system reconfiguration at disturbance (Westkämper et al. 2000, p. 25). Flexibility is, thus, one *class of changeability* (H-P. Wiendahl 2002, p. 126). Altogether, there are five classes of changeability defined (Figure 3.2): *agility*, *transformability*, *reconfigurability*, *flexibility*, and *changeover ability*. Their hierarchical structure corresponds to the production system hierarchy[68,69], and any given level of changeability encompasses those below it. On the relevant level of the production system, changeability is achieved through flexibility and reconfigurability[70]. (ElMaraghy et al. 2009, pp. 11–13)

3.1.1.1 Flexibility

There are numerous ambiguous and partly conflicting definitions of flexibility (Narain et al. 2000, pp. 202–203; Sethi et al. 1990, p. 289; de Toni et al. 1998, p. 1587; Shewchuk et al. 1998, p. 325). Most have in common that they see flexibility as the ability to adapt (reversible) to altered constraints or requirements (Schauerhuber 1998, p. 51; Kaluza 1993, p. 1173). Hence, flexibility can be characterized by its principal ability, speed, and degree of adaptation (Corsten et al. 2012, p. 14). An alteration of constraints or requirements happens in the dimensions of the product lifecycle, process (product variants and batch

[68] Tables B.1 and B.2 (Appendix B) give a detailed overview of production system hierarchy definitions.

[69] Even in times of hierarchy-free production systems associated to I4.0, the given definition of changeability is applicable, as the purely logic description of the RAMI4.0 (DIN SPEC 91345) describes any layer of its architecture axis with respect to classical levels of the automation pyramid.

[70] Changeability was previously understood as a combination of flexibility and responsiveness (H-P. Wiendahl et al. 2005, p. 71; Reinhart et al. n.d.), with response capability to be achieved by a reconfiguration of modules, mainly in organization and machinery (Reinhart et al. 1999a, p. 22)

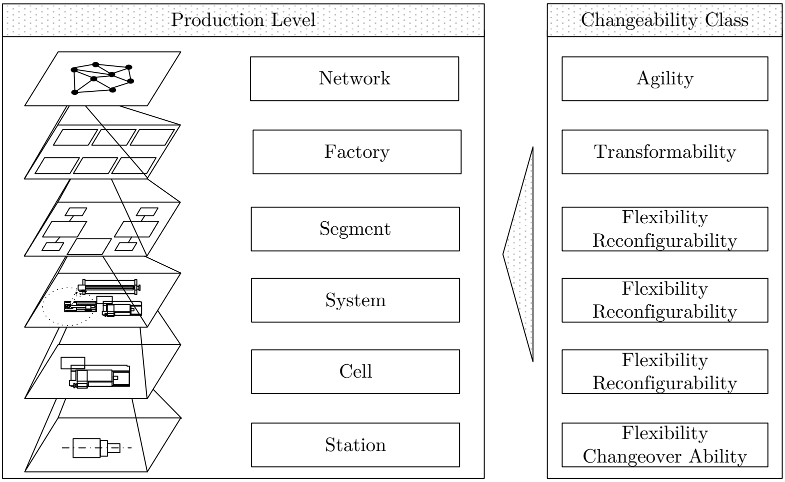


Figure 3.2: Corresponding hierarchies production & changeability (ElMaraghy et al. 2009, p. 11)

size), operation (part spectrum and tasks), volume (unit fluctuations), capacity expansion, time, cost, and quality (Schenk et al. 2014, p. 41; Nyhuis et al. 2010, p. 8; Abele et al. 2006, p. 434; Cisek et al. 2002, p. 442; de Toni et al. 1998, p. 1591). Flexibility is seen as an absorber of uncertainty, effective within a range of reachable states, with limited cost and time needed to move between states (de Toni et al. 1998, p. 1589).

Flexibility definitions are primarily distinguished by the effective moment of adaptation in relation to an alteration of constraints or requirements[71]. Numerous authors understand flexibility as a proactive adaptation (Schenk et al. 2014, p. 498; Grundig 2013, p. 33; ElMaraghy et al. 2009, p. 4; Nyhuis et al. 2008a, p. 87; Denkena et al. 2005, p. 70; Zäh et al. 2005, p. 2; Westkämper et al. 2000, p. 24; Schmigalla 1995, p. 328; Mandelbaum et al. 1990, p. 17). Other authors add reaction as inherent part of flexibility (Kaluza et al. 2005, p. 9; Voigt et al. 2007, p. 46; Fleck 1995, p. 195; Oelsnitz 1994, 71+q). The latter is sometimes referred to as dynamic flexibility, as opposed to static flexibility in defining the proactive concept (de Toni et al. 1998, p. 1590).

Proactive flexibility holds resources constantly available, to be used ad hoc whenever necessary. The flexibility range addresses a predicted adaptation and is, thus, limited to options envisioned at the time of the system design. As resources are also bound when unused, it is impossible to share them between different production activities. In *reactive*

[71] Horstmann (2007, p. 13) identifies in the literature further distinctions of an effective planning horizon (strategic vs. operational), effective duration (long vs. short), effective intention (offensive vs. defensive), effective type (quantitative vs. qualitative), and effective domain (external vs. internal).

flexibility, on the contrary, active measures are taken after the change trigger. Resources are not tied upfront, which entails the risk that an adaptation cannot be performed promptly. (Abele et al. 2011, p. 19; Grundig 2013, p. 33; Horstmann 2007, pp. 14–15; Denkena et al. 2005, p. 70; Westkämper et al. 2000, p. 24)

Browne et al. (1984a, pp. 1-4; 1984b) introduce eight types of flexibility - *machine flexibility*, *process flexibility*, *product flexibility*, *routing flexibility*, *volume flexibility*, *expansion flexibility*, *operation flexibility*, and *production flexibility*[72] - as a standard for the classification of FMS. Based on a literature review, Sethi et al. (1990, pp. 310–313) add the additional aggregate types of *market* and *program flexibility*, and *material handling flexibility*[73].

An alternative classification of flexibility is suggested by Eversheim et al. (1983, p. 27)[74]. They introduce the period-oriented *changeover* and *reconfiguration flexibility*, the date-oriented *routing* and *operational flexibility* and the incident-oriented *failure flexibility.*

While Browne et al. put focus on the objectives of flexibility to build their types of flexibility, i.e., what the flexibility is used for, Eversheim et al. (with the exception of the incident oriented failure flexibility) focus on the means by which flexibility is achieved. The resulting flexibility types are, however, related (Figure 3.3):

- Change-over and reconfiguration flexibility match product and expansion flexibility.
- Failure flexibility is, per definition, part of Browne et al.'s routing flexibility.
- Eversheim et al.'s routing flexibility is needed for process, material-handling, and operation flexibility.
- Operational flexibility describes the degree of universality of a machine to achieve volume and machine flexibility.

[72] *Machine flexibility* measures the ease of changing between a given set of part types on one machine. *Process flexibility* describes the mix of different part types that a production system can process without changing the setup of the system. This variant-mix flexibility is also referred to as *job flexibility* (Buzacott 1982, p. 15) and *mix flexibility* (Gerwin 1982, p. 114). *Product flexibility* is achieved by taking actions (Mandelbaum 1978, pp. 616–617) to changeover from one product to a new (set of) product(s), quickly and economically. *Routing flexibility* refers to the production system's capacity to steer production orders on different routes through the system. Routing flexibility is applied in two ways: Orders are rerouted as part of a failure strategy, to avoid broken equipment; independent of breakdown situations, similar parts are processed on different routes through the systems to achieve a high utilization of system elements. *Volume flexibility* stands for an inherent system characteristic to remain profitable on different operating points of production volumes, without having to reconfigure the system. *Expansion flexibility*, on the other hand, is used for a modular and simple expansion of the system, when the capacity limit of the system is reached. *Operation flexibility* is associated with the a product's architecture or the shape and finish of a part. It describes the ability of interchanging the order of manufacturing activities, in consideration of a needed sequence of operations. *Production flexibility*, finally, is the aggregate flexibility of the production system to efficiently produce different volumes of a diversity of parts, i.e., product variety (K. Ulrich 1995, p. 10). (Browne et al. 1984b)

[73] *Market* and *program flexibility* reflect how easily a production system can adapt to changing market environments and how long it can run virtually untended. *Material handling flexibility* refers to the ability to move parts efficiently within and in between station or machines on flexible routes.

[74] Eversheim et al.'s flexibility types are defined for assembly systems.

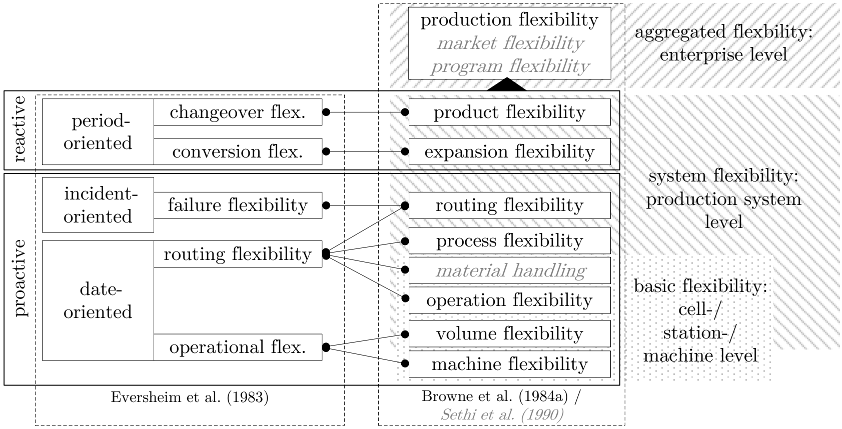


Figure 3.3: Flexibility types of production systems

From a system hierarchy perspective, machine flexibility is clearly allocated to lower system levels. Routing and process flexibility are achieved on the production system level. Material-handling, operation, and volume flexibility influence the production system level and its subordinate levels. All those flexibility types are necessary for the aggregated production, market, and program flexibility, on superordinate enterprise system levels.

Product and expansion flexibility need actions to activate them. Consequently, they are period-oriented, reactive flexibility concepts. All other flexibility types are incident- or date-oriented, proactive flexibility concepts.

Like the definition of flexibility itself, the understanding of what belongs within the scope of a flexible system adaptation also differs among various authors. In line with their proactive flexibility understanding, a flexible system adaptation only happens on the system level of processes, according to Schmigalla (1995, p. 328) and Schenk et al. (2014, p. 498). The number and relation of production system elements cannot change. Hernández (2003, pp. 44–45) additionally allows a change of relations between the elements, with an otherwise unchanged system. ElMaraghy (2005, p. 270) introduces the differentiation between a soft and a hard system adaptation. A soft adaptation is achieved by rerouting, rescheduling, replanning, reprogramming, or augmentation of people, time, or subcontracts. During a hard system change, system elements may be added, removed, substituted, and relocated within the layout. She calls the soft system adaptation flexibility, and the hard physical modification is termed a system reconfiguration. Finally, K. Ulrich (1995b, p.10, 12) points out that flexibility resides in the architectures of products rather than in the production system alone. He states that the combination of a modular product architecture with high process flexibility can lead to a make-to-order component fabrication of infinite variety.

3.1.1.2 Reconfigurability

Reconfiguration is defined as a reactive (manual or automatic) adjustment of a production system or machine structure, in order to respond quickly and with little effort to changing market requirements or system failures. Its roots are the design of Reconfigurable Machine Tools (RMTs), built of reconfigurable, independently functional, modular machine components. The adjustment is achieved by a change of arrangement and connections of functional system elements; addition, removal, and interchange of functional system elements; or a reconfiguration of the functional system elements themselves. (H-P. Wiendahl 2002, p. 127; Koren 2010, pp. 210–226; Koren 2007, pp. 27, 32; ElMaraghy 2005, pp. 262, 266; H-P. Wiendahl et al. 2014, p. 128; Suh 1998, p. 200; Koren et al. 2010, pp. 131–132; Mehrabi et al. 2000, p. 1)

Other than in flexible systems which feature a high built-in functionality capacity and functionality of reconfigurable systems are not fixed. An open software architecture and a modular setup of hardware enable the system to provide customized flexibility. (Mehrabi et al. 2000, p. 404; ElMaraghy 2005, p. 265)

Reconfigurable Manufacturing Systems (RMSs) possess the following six key characteristics to enhance productivity, reduce life cycle cost, and ensure a rapid and efficient reconfiguration (Koren 2007, pp. 37–39; ElMaraghy 2005, p. 265; Mehrabi et al. 2000, p. 407; Koren et al. 2010, p. 132; H-P. Wiendahl et al. 2007, pp. 787–788):

- *modularity*, to enable the change of the system structure[75]
- *integrability*, for ready integration and future introduction of new technologies
- *convertibility*, for quick product changeover and the integration of new products
- *diagnosability*, to identify sources of quality and reliability problems
- *customization*, to match system capabilities and flexibility to the application
- *scalability*, for incremental, rapid and economical change of capacity

ElMaraghy et al. (2009, p. 16) distinguish Reconfigurable Assembly Systemss (RASs)[76] from RMSs by the additional characteristics of *mobility*, and *automatibility*.

The characteristics are divided into essential (customization, scalability, and convertibility) versus supporting (modularity, integrability, diagnosability) features. The latter support rapid reconfiguration of a production system but do not guarantee a modification of capacity and functionality. (Koren et al. 2010, p. 132)

[75]Modularity plays a key role in enabling a system to make adjustments (Abele et al. 2006, p. 435). Modular production systems with flexible routing can generally be converted at lower effort and cost (Figure **??**), because it is possible to replace system elements independently.

[76]ElMaraghy et al. (2009) omit diagnosability and integrability from their list of RMS characteristics.

Changeability enabler	Characteristics of RMS/RAS	Type of Enabler
Universality Scalability	Convertibility Scalability	Inherent characteristic of system (element)
Modularity Mobility Compatibility	Modularity Mobility Integrability	Interface to environment of system (element)
	Customization Diagnosability Automatibility	— — —

Table 3.1: Typification of changeability enablers

The characteristics of reconfigurable systems (ElMaraghy et al. 2009, pp. 15–19) are related to the changeability enablers (H-P. Wiendahl et al. 2007, pp. 787–788) (Table 3.1)[77]:

- Scalability, modularity and mobility are listed in both categories.
- Universality and convertibility both allow a switch between product variants with the integration of additional machine components and functions into system elements.
- Compatibility and integrability both foster the reconfiguration of modules by standardization of interfaces and general integration methodologies.

Customization, diagnosability, and automatibility do not have a matching changeability enabler (Table 3.1), due to the following characteristics:

- Customization is a consequence of reconfigurability.
- Diagnosability is a characteristic that any production system should have, independent of its changeability.
- Automatibility is influenced by product and process features and intended to be used for quality, ergonomics and economical reasons.

3.1.1.3 Conclusion on changeability terminology

From these given definitions, the following conclusion is drawn regarding the terminology of changeability as a basis for the subsequent works of this thesis: For a production system, flexibility and reconfigurability constitute changeability (Equation 3.1 and Table 3.2).

$$Changeability \quad = \quad Flexibility \quad \cup \quad Reconfigurability \tag{3.1}$$

[77]The definitions of Koren (2007, pp. 37–38) and H-P. Wiendahl (2014, p. 133) of universality and convertibility and of compatibility and integrability are used for the comparison.

	Changeability	
	Flexibility	**Reconfigurability**
Effective moment	Proactive	Reactive
Effective means	Switchover Flexible routing	Changeover Conversion of elements
Effective enablers	Universality Scalability	Modularity Mobility Compatibility
Effected structure	Relations	Elements
Effected objectives	Product mix flexibility	Short lead time capability
	Volume scalability	
	Product variety	

Table 3.2: Summary of conclusions on changeability terminology on production system level

Flexibility is understood as a proactive concept, with pre-invested capabilities and resources to adapt a system within predefined ranges to known or anticipated requirements. Reconfigurability is understood as a reactive concept enabling the production system to change its structural concept and thus move the above-mentioned flexibility ranges to different levels.

Consequently, a *switchover* between different points of operation of output volume and between different product variants without structural changes is seen as flexible adaptation of a production system. Likewise, *alternative routes* through the system to vary process, material handling or operation sequence or to react to failures belong to flexible adaptations. A change of a system by *changeover* or *conversion* is, on the contrary, categorized as reconfiguration. It is the objective of a reconfiguration process to integrate or disintegrate functional abilities that are needed for product variety or manufacturing technologies or to expand or downsize a system's capacity.

According to this categorization, a flexible system adaptation alters the system only in regard to relations between the systems' elements (i.e. flexible routing). A reconfiguration, however, may substitute, relocate, add, or eliminate system elements (i.e. expansion, downsizing, system changeover). It may, furthermore, change a system's element internally (i.e. element changeover).

Furthermore, since they are inherent characteristics, the changeability enablers of universality and scalability make a system flexible. Modularity, mobility, and compatibility, which describe the ability to built an interface with a surrounding environment, enable a production system to reconfigure.

Finally, the changeability objectives of personalized production systems are associated:

- Volume scalability and product variety are supported by flexibility and reconfigurability, depending on the relationship between requirements and flexibility ranges of the system.
- Product mix flexibility is achieved through the flexibility of the system.
- Capability for short lead times and the possibility of gradual investments are achieved through the reconfigurability of the system.

3.1.2 Current approaches to design changeable production systems

Previous works on the design of changeable production systems, specifically their organizational structure, can be clustered into three groups (Figure 3.4):

1. Basic literature on the design of factories and production systems
2. Research on the design of changeable production systems, tailored to the previous production paradigm of mass customization and coupled production lines
3. Research on reconfigurable, flexibly linked production systems

These works are introduced in detail in the following.

3.1.2.1 Foundations of factory planning and production system design

The basics of factory planning (Ammer et al. 1986, p. 161; Aggteleky 1990, p. 441; Felix 1998, pp. 123+; Schraft et al. 2014, p. 10.44; VDI 5200-1; Schenk et al. 2014, p. 320; Pawellek 2014, p. 237; Grundig 2015, p. 132) and production system design (Bullinger 1986, p. 147; Eversheim 1989; Lotter 1989, p. 304; REFA 1990, pp. 84+; Dangelmaier 2001; Konold et al. 2009, p. 32) are still valid as a general basis. They don't deliver actual design methods for a production system design and the older of these publications address changeability only by the aspect of flexibility.

3.1.2.2 Design of changeable production systems for mass customization

A traditional concept of a modular production system is that of **group technology**, also referred to as **cellular production**. Group technology is the technical realization of the classical organizational structure of the production group. It divides factories in groups of machines and associated product families with no backflows and crossflows (Burbidge 1991, p. 5). To design group technology systems, the so-called cell formation problem is solved with a process operation sequence or production flow analysis of existing systems[78]

[78]The identification of product similarities traces back to work piece classification systems of form and feature for machining (Opitz 1966; Opitz 1968). Methods, solution approaches and models (e.g., graph

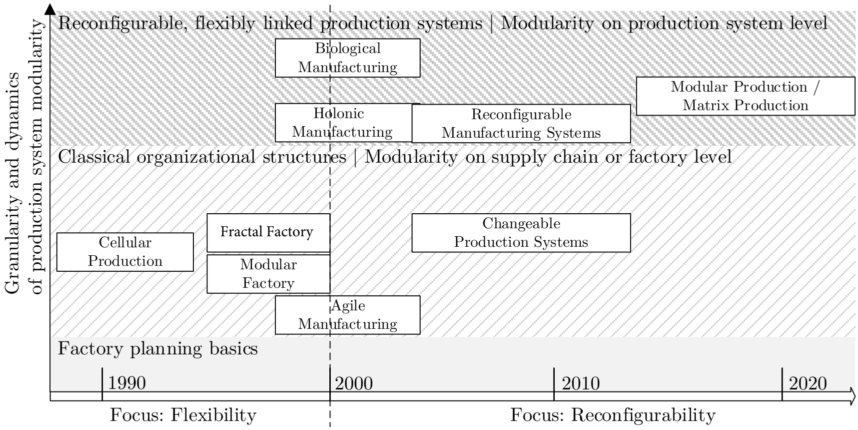


Figure 3.4: State of the art approaches for the design of changeable production systems

(Ahkioon et al. 2009, pp. 1574–1575). A well-known instantiation was the Volvo Uddevalla factory which divided the overall car assembly into four team zones[79] (Ellegård 2007, p. 48).

It could be argued that a system of flexibly linked process modules has similarities to a large production group. The clustering of products according to process similarities is, thus, interesting for the design of reconfigurable flexibly linked production systems. Classical production groups, however, usually combine single-purpose machines. Self-organization is used to control the processes within the group, which limits the size of the production groups. There is no focus on the level below the individual groups. Furthermore, cellular production systems are designed for limited product types in predictable market conditions (Abdi et al. 2003, p. 2274). As a consequence, the problem of disharmonized capacity requirements between different groups is not in the focus of the functional cell formation approaches. Finally, it might be difficult to cluster personalized products from a product/process view by similarity, given that the option of individualized components potentially require differing special technologies within one product family.

The concept of **agile manufacturing** was brought forward by the Intelligent Manufacturing Systems (IMS) initiative.[80] Agile companies attempt an intensive internal

theoretical methods, cluster analysis, pattern recognition) as well as the use of similarity coefficients for the cell-formation problem are discussed in Ahkioon et al. (2009, pp. 1574–1575) and Yin et al. (2006).

[79]The setup of the team zones offered very high product flexibility but almost no process flexibility, which prevented automation. Uddevalla production was terminated for that reason. (Greschke 2016, p. 80)

[80]IMS was a global initiative for manufacturing technologies and systems development (Parker 1998, p. 519).

and external cooperation within an integrated value chain, to offer individual products to customers in arbitrary lot sizes (Goldman et al. 1995, pp. 73–74). The IMS project **HIPARMS** suggested an agile production system framework, including technology, organization structure and personnel utilization (CORDIS 2002). The main focus was the incorporation of new technologies (i.e. machining tools) into production systems (Fukaya 2004, p. 8). All in all, publications on agile manufacturing do not offer design methods or guidelines to design factories and processes; they focus on supply chain relations and the utilization of employee knowledge and creativity (H-P. Wiendahl et al. 2014, p. 104).

The organizational concepts of the **modular factory** (Wildemann 1998) and the **fractal factory** (Warnecke 1996; Warnecke 1995) finally mark a change from a purely technological production system segmentation to a market and customer orientation. Both define factories as structures of autonomous modules (Wildemann 1998, p. 57; Warnecke 1996, pp. 141–142). Fractals are inspired by fractal geometry, i.e. each subsystem maps the complete structure of its superordinate fractal (Warnecke 1996, p. 137). Fractals are interconnected and their main characteristics are self-organization, self-similarity, and dynamics of structure (Warnecke 1996, pp. 140–141). Waltl et al. (2015, p. 23) further evolved the modular factory with the introduction of value-stream-oriented segments as *factories within the factory*. They are product-oriented, responsible for cost and profit, contain several stages of the supply, and have indirect functions.

Both the modular factory and the fractal factory gave important stimulus for the decentralization of factories (H-P. Wiendahl et al. 2014, p. 12). Wildemann (1998, p. 131) offers design criteria (such as flow-orientation and harmonization of capacities and lot sizes), but is limited to classical organizational structures. His generic design process remains product-driven, starting with a vertical and horizontal segmentation of the product spectrum (Wildemann 1998, pp. 344, 357). Warnecke (1996, p. 151) does not rely on a pure product segmentation but uses cluster analysis to identify similarities of products and processes to define fractals. The fractal factory's production system level is, nevertheless, organized using classical organizational structures (Warnecke 1996, p. 155). Waltl et al. (2015, pp. 140–198) applied the modular factory concept for the automotive industry. They built a model of a modular factory with a generic description of production system levels and functions but did not develop a design method.

In the tradition of the fractal factory, the **Stuttgart Enterprise Model** (Westkämper 2006b; Westkämper et al. 2009b) adds a technical perspective to the organizational focus. Terminology and concepts are defined for the design of **changeable production enterprise systems**. Tailored to mass customization, all associated works on production system design contain coupled production lines as the layout paradigm: Küber (2017) and Aisenbrey et al. (2015) concentrated on the configuration of modular production lines.

Landherr (2014) matched products and production lines with the help of ontologies. Kluge (2011) designed modular production lines by a comparison of functional requirements with assembly functions. Löffler (2011) offers a comprehensive design of a structural production system concept, but her focus is the factory (e.g. site) level within a production network.

Fundamental works on **changeable production systems** have been carried out at **IFA Hanover** (H-P. Wiendahl et al. 2005; H-P. Wiendahl et al. 2014, pp. 117–148). The members of the research group first focused on the context of factory planning. Hernández (2003) introduced and defined the changeability enablers.[81]. Harms (2004) suggested periodic structural design on the production system level using a coordination agent. He identified the necessity for reorganization based on a rating of material and information flow. Nofen (2006) introduced a control-cycle-based transformation process. Klemke (2014) derived change potentials through change monitoring and qualitative evaluation of changeability. Neither of the three gave directions on how to design the structural system concept. Wagner (2012) developed a method for a continuous design of scalable production stages using a multistage control loop model. He applied AD to design scalability measures and evaluates with logistical performance indicators. With his focus on scalability, he narrowed his work on the capacity factor of changeability only. Pachow-Frauenhofer (2012) developed a model of change as a control loop, in which changeability is described as a vector of quality, time, cost, and product variety. She uses the model to evaluate the selection of alternative technical equipment for different setups of conventional production lines.

The study on changeable production systems **WPS** (Nyhuis et al. 2008b), as well as the subsequent research project **WaProTek** (Nyhuis et al. 2013), transformed IFA's factory planning focus to the production system level. WPS and WaProTek built upon traditional organizational structures. They focused on the structural design of process modules[82] for manual assembly and logistics processes, designed by a comparison of target characteristics with functional suitability (Baudzus et al. 2013).

In the 2010s, various research projects on the topic followed: **ProAktiW** attempted to enable a changeable production system design at the technological and organizational level (Kampker et al. 2013, p. 1). The focus centered on the technical design of processes, equipment, and workforce qualification concepts (S. Heinen et al. 2013).

WaMoPro (Kreimeier et al. 2013) pursued changeability through a holistic modularity of technology, organization, and staff (Meier et al. 2012, p. 184). The project developed a library of modules to (re-)configure production systems (Schröder et al. 2013, p. 119; Meier et al. 2013a, p. 493; Meier et al. 2013b, p. 1011). The focus centered, however,

[81]Compare section 3.1.1 for the introduction of changeability enablers. In Hernández (2003, p. 54), compatibility was still separated into ability to interconnect and ability to (dis-)integrate.

[82]The definition of an assembly process module by Slama et al. (2004) is taken as a basis.

on self-assessment and a pre-alert of change-affecting factors that identify the need for reconfiguration (Meier et al. 2008, p. 58; Velkova 2014).

RePlaMo also applied modularity to develop reconfigurable platform concepts for assembly cells of a scalable degree of automation (Spath et al. 2013, p. 7; Brecher et al. 2013b, p. 35; Brecher et al. 2013a). Modules are operating resources with responsibilities for certain tasks (R. Müller et al. 2011b, p. 602; R. Müller et al. 2011a, p. 3). Eilers (2015) extended RePlaMo's reconfiguration concepts from the cell to the production system level, but only for the classical organizational concepts of assembly groups and coupled assembly lines.

PlaWaMo wanted to adapt assembly systems by changing between different system setups. The adaptation need is evaluated scenario-based (R. Müller et al. 2013, p. 364), and setup alternatives are selected from a catalogue of evaluation criteria (Reinhart et al. 2013, p. 307; Backhaus et al. 2012, p. 340). One result of the PlaWaMo concept is the decomposition of assembly tasks into basic functions and the assignment of components to each function which are then combined to submodules of an assembly system (Hees et al. 2012, p. 541). PlaWaMo's design approach is, however, product-driven (Klein et al. 2017, p. 176) and the underlying structural concepts are the classical organizational structures (Riegel et al. 2013, pp. 107–109; Jaudas et al. 2013, p. 147; Backhaus et al. 2012, p. 340).

3.1.2.3 Design of modular, flexibly linked production systems

As part of the IMS initiative, the concepts of **Biological Manufacturing Systems (BMS)**[83] and **Holonic Manufacturing Systems (HMS)** were developed. **BMS** adapt the behavior of biological organisms to achieve self-organizing and reconfigurable systems (Ueda et al. 1994, p. 76). Line-less production is proposed as an implementation of BMS (Ueda et al. 2001). The BMS concepts foresee all production entities (i.e. workers, operative resources, and processed goods) to be freely moving distributed objects. They are matched locally to perform a manufacturing process according to capabilities and on demand (Ueda et al. 2001, p. 320). The main interest of BMS researchers was the conception of matching technologies.[84] Initial system configuration and reconfiguration during operation are described, with a layout focus only (Car et al. 2004, p. 23). BMS have been validated in case study simulations (Ueda et al. 2001; Ueda et al. 2002) but have never been transfered into industrial application (Löffler 2011, p. 35).

[83]Tharumarajah (2003) explains the differences of BMS organisms, manufacturing holons, and fractals. He notes that BMS are referred to as *Bionic*, instead of *Biological Manufacturing Systems*, by some.
[84]Production entities are modeled as connected CPSs: Potential fields are generated by each machine to attract products on AGVs, which are sensing the fields (Ueda et al. 2001, p. 320).

HMS are built by a conglomerate of specialized, autonomous, decision-making manufacturing holons[85] of the four basic types of product, order, staff, and resources (Tharumarajah 2003, p. 21). HMS design methods work incremental and from the bottom. Manufacturing holons are identified by their general responsibility (instead of precise function) and designed in detail with a focus on autonomy, cooperation capability, and reusability. The system is then configured with those functionally predefined production system units (van Brussel et al. 1999, p. 39). The authors assume that even resource holons can be altered on a daily basis. HMS seek high flexibility in structure and operation, but they have only been implemented in part as a highly distributed control paradigm (van Brussel et al. 1999, p. 35) and as a framework to build research consortia (H-P. Wiendahl et al. 2014, p. 110).

One of the early works on **Reconfigurable Manufacturing System (RMS)** was published by Pouget (2000) as a technological concept for modular and autonomous production machinery, to enable the automated production of a high number of variants in small and medium volumes. Pouget (2000, p. 84) decomposes the production processes through object-oriented software development techniques. He further develops a database of autonomous production modules (APM) to be supplied by a leasing pool which are rated using a qualitative reconfiguration index (Pouget 2000, p. 146). Pouget (2000) concentrates on the development of technical production resources, not on the production-system level.

Koren (2010) propagates RMS with his concept of production systems of adjustable structure and machines, in order to achieve scalability of throughput capacity and changeable functionality (Koren et al. 1999, p. 528). His group researches configuration and conversion of manufacturing systems (Maier-Speredelozzi et al. 2003, p. 367; Koren et al. 2010). General layout concepts of symmetric and asymmetric machine arrangements are conceptualized in which parallel CNC machines are assigned to different stages as demanded by capacity (Koren et al. 2010, pp. 134–137). Albeit Koren et al. (2010, pp. 139–140) examine challenges and possibilities of using their RMS concept for Reconfigurable Assembly Systems (RAS), they don't develop specific solutions to configure RAS.

The group of ElMaraghy builds on Koren's work on RMS: Youssef et al. (2006) and Youssef et al. (2007) introduce a period of ideal capacity and functionality configuration. They work with a flow machining line of multiple, similar stations, connected in parallel at different stages. Navaei et al. (2014) develop algorithms to group product variants by commonality in terms of using identical machines. The approach is tailored for product design modifications and PPC. Manns et al. (2008) examine the topology of RAS, although

[85] The term holon was made up by Koestler (1989). It stands for a sub-whole or part, that can act autonomously and cooperatively.

they only consider the machining processes before assembly for the functional segmentation of the system.

There are further independent works on reconfigurable production systems: Colledani et al. (2005) split the production system into dedicated manufacturing machines, flexible manufacturing machines, assembly machines, and disassembly machines, and model buffers as pseudo machines for simulation. Their subject of interest is material flow, not system design. Drabow (2006) creates a system of production modules and combines different organizational structures into segments with flexible relations between the modules as well as into coupled segments for the production of standard products. His focus is the design of these production modules tailored for machining technologies, and their evaluation regarding the change drivers. Matt (2002, 2013) researches the design of reconfigurable production systems in the tradition of the modular factory. He develops guidelines for the (re-)design of scalable assembly systems. His layout configurations allow for a swift and cost-efficient adaptation to volume and variations. The configuration follows a classical design approach of product-driven clustering and output-rate-defined cycle time calculation, limiting the production system design to the variants of one family.

Based on the concept of reconfigurable production systems, various research projects have started to investigate **modular assembly systems** with flexibly linked stations, lately referred to as **matrix production**: Greschke (2016) delivers a comprehensive description of the concept of matrix assembly systems in the automotive industry. He suggests a system of flexibly linked stations, coupled by AGVs, in a bypass layout. Order control and material supply are selected from a morphology of conventional strategies. Greschke's design method functions capacity-driven: Work content is assigned to assembly worker capacities, aiming at an average system cycle time. Differing process times are weighted for assignment. A priority station (and worker) is defined for each process. Stations are configured with an equipment combination matrix, the layout is derived with the help of a transport intensity matrix. (Greschke 2016, pp. 86+)

The mean system cycle time of Greschke's approach allows for a harmonization of otherwise cycle time-independent work stations. His capacity orientation, and, specifically, the weighted process time priorities of work stations limits variant mix flexibility. He acknowledges research approaches of varying operation sequence but excludes this from his approach, thus losing the potential to utilize the assembly sequence flexibility inherent in the product architecture. Greschke defines the sequence of operations "successively" (Greschke 2016, p. 106), presumably relying on a conventional assembly order[86].

Large parts of the research for this thesis has been done within **ARENA2036**, a Stuttgart-based research platform that aims towards the development of decoupled, fully

[86] Greschke (2016) cooperates with the Volkswagen AG for his PhD project.

flexible and highly integrated production systems built from process modules for defined assembly and manufacturing operations (Bauernhansl 2015, p. 1153). Diverse topics are investigated by the ARENA2036 research group. Fechter et al. (2016) configure human-robot collaborative assembly process modules in a flexibly linked layout, applying AD. Popp (2018, pp. 85–91) acknowledges the impossibility of knowing in advance at what exact time and order a certain operation will be done in a system of flexibly linked process modules and develops appropriate *just-in-real-time* material supply concepts. W. Kern et al. (2017, 2016, 2015)[87] develop a design method for modular automotive assembly systems. The system design is based on a flexible routing between decoupled stations, a variant-defined assembly sequence, and an individual cycle time for each station. Stations are functionally defined by an assignment of assembly operations. The method of W. Kern et al. is product-driven. The functional definition of the stations is determined by segmentation of assembly operations along the assembly precedence graph, considering the flexibility of operation sequence, inherent in the product architecture.

The project **SMARTFace** promotes a changeable system of flexibly linked stations for the assembly of electric cars (Bochmann et al. 2016, p. 175). SMARTFace follows three basic principles for system design: batch production, autonomous working groups, and a segmentation into fractals (Böckenkamp et al. 2017, p. 546). The layout of assembly stations and the assignment of processes is conceived by scenarios (Bochmann et al. 2016, p. 183). The major part of SMARTFace, however, then concentrates on the self-control of production orders in a decentralized PPC (D. Müller et al. 2019; D. Müller et al. 2018).

The project **freeMoVe** (Lettmann et al. 2019; Göppert et al. 2018) uses the paradigm of flexibly linked assembly resources to enable a production system for a short-term integration of new products and for scalability. The research of freeMoVe concentrates on the routing of different production orders by matching status, functions, setup, and operative cost of flexibly linked assembly resources with the respective needs of an order, applying cluster analysis. The system design is taken as a given input.

3.2 Evaluation of production performance

3.2.1 Performance, efficiency and productivity

Efficiency is defined as the potential of profitably used input factors to reach a certain output. Production efficiency relates resource utilization to a potential maximum capacity of a production technology. In an efficient production, it is impossible to produce more

[87] W. Kern cooperates with the Audi AG for his research. He is not a member of ARENA2036 but associated with the research group through his affiliation with a graduate school of the University of Stuttgart (GSaME).

of at least one product without increasing the input or reducing the output of all other products for given resources and technologies[88]. (Feess et al. 2017; Sickles et al. 2019, p. 97)

Productivity, on the other hand, quantifies the output of produced goods, in relation to the input of production factors[89] regardless of potential maximum performance. It is expressed as accomplished volume-per-input or value-per-input factor over a period of time. (Sickles et al. 2019, p. 97; Voigt et al. 2017; H-H. Wiendahl 2011, p. 116)

The relations are as follows (Equation 3.2):

$$Efficiency = \frac{Output}{Potential\,Output}[\%] \qquad Productivity = \frac{Output}{Input}\left[\frac{1}{time, \$}\right] \tag{3.2}$$

3.2.1.1 Conclusion on production performance terminology

Both efficiency and productivity express the performance of a production system (Sickles et al. 2019, p. 97). Consequently, both may be applied as key indicators for performance evaluation of a production system. They differ, however, in their analytical focus:

Efficiency is a normative concept. It indicates the residual performance contingent of a certain production system setup in a given status. It is a good evaluator of how well a system is performing under differing circumstances.

Productivity describes a performance status. It is suitable for a relative comparison of different production system setups using both logistical as well as monetary figures. For logistical performance, output and input may be quantified as a numbered amount of goods. To evaluate performance from a return-on-investment viewpoint, input may be quantified as monetary expenditures to achieve the output.

Productivity is more appropriate for production system design for which the comparison of different design embodiments is vital. Furthermore, at the time of a system design, an actual output of a production system can only be predicted. A comparison of different design embodiments in terms of productivity is possible through the systems' potential outputs which can be calculated, or at least be simulated.

[88]This equilibrium is referred to as Pareto Koopmans efficiency. (Sickles et al. 2019, p. 64)

[89]In the case of total productivity, not only one but all aggregated production factors are taken as an input for the calculation. Total productivity is used for comparisons of international GDPs. As a measurement for production performance, partial productivity is usually applied. (Voigt et al. 2017)

3.2.2 Current approaches to evaluate production system design embodiments

Common evaluation techniques in production system design can be classified into several categories:

1. value quantification
2. classical capital budgeting
3. modern, life-cycle-oriented investment and costing
4. KPI

In the following, the different techniques are reviewed for their suitability to evaluate a system's potential productivity during a design phase.

3.2.2.1 Value quantification approaches

The **value-benefit analysis**, the **cost-utility analysis** and the **decision tree** are common evaluation and decision-making techniques in factory planning (H-P. Wiendahl 2014, p. 9.10). They all share the goal to quantify the value of a certain solution.

The **value-benefit analysis** (Zangemeister 2015) utilizes a subjective quantification by experts. Solutions are rated according to their fulfillment of weighted evaluation criteria. It is intuitive in its application but lacks objectivity in the evaluation.

The **cost-utility analysis** rates benefit and cost of an investment against each other. It is similar to the net present value method, with the difference that it quantifies non-monetary decision criteria in a monetary dimension (Heger 2007, p. 50). Drabow (2006, pp. 119–122) broadens the cost-utility analysis with a risk-level assessment to help justify additional expenditures into changeability. The challenge is that a reasonable monetary dimension to express a benefit cannot always be found. Drabow solves the problem by using very broad general benefit categories, with the drawback that different investment alternatives within one category are hardly distinguishable from each other.

A **decision tree** is an explanatory model that maps a limited number of states, their probability of occurrence, and possible subsequent decisions in a directed graph. It is not a suitable concept to be applied in production system design, since the number of decision options exceeds a reasonable amount. (Heger 2007, p. 45)

3.2.2.2 Classical capital budgeting techniques

Capital budgeting appraises the profitability of an investment project to facilitate an investment decision (Wöhe et al. 2000, p. 621). Classical capital budgeting techniques are accordingly tailored to judge economic efficiency. The **payback period** method and the

net present value calculation are particularly useful for the comparison of investment alternatives (H-P. Wiendahl 2014, p. 9.28).

The **payback period calculation** estimates the effect of an investment on a firm's liquidity (H-P. Wiendahl 2014, p. 9.28). An amortization period is calculated by dividing an investment capital through its predicted yearly benefits (Pouget 2000, p. 31). The prediction is difficult in a volatile business environment. Furthermore, the calculation scheme dictates a one-time investment and a constant production program of variants and volume which doesn't reflect the operative reality in which requirements may change in a shorter period of time than its investment amortizes (Witte et al. 2013, p. 319).

The **net present value method** discounts all positive and negative cash flows onto the effective date of an investment (H-P. Wiendahl 2014, pp. 9–28). Thus, it provides for a comparison of investments, with cash flows spread over time (Wöhe et al. 2000, p. 637). This makes it in principle well-suited for the evaluation of system reconfiguration with its partial investment also spread over time. Heger (2007, pp. 110–125) applies the net present value method to evaluate the changeability potential of factories from an economic point of view. He attempts to describe future developments with expectation value and standard deviation. However, the method works with an invariable rate of return (Heger 2007, p. 40) and it also requires the difficult prediction of time and type of reconfiguration (Witte et al. 2013, p. 320; Möller 2008, p. 35; Baecker et al. 2003, p. 22).

3.2.2.3 Life cycle-oriented cost modeling

Recently, **life cycle-related cost and investment calculations** of economic efficiency indicators have been suggested: Witte et al. (2013) use different future scenarios to predict future employment of resources with consideration of changes in the production program and in the product spectrum during a resource's life cycle. Sesterhenn (2003, p. 33) continues the previous works of Briel (2002) and Osten-Sacken (1999): He delivers a cost model for flexible and reconfigurable production systems that allows positive and negative investment cash flows during the complete life cycle of the reference object. He builds scenarios for the development of production volumes, the efficiency of production technologies and the price of resources. Neither of the two approaches solve the problem that decisions are taken on the basis of scenarios for an unpredictable future.

Another life cycle-considerate approach which has become particularly popular in research, is the **real option analysis** (Wang 2008; de Neufville 2003; de Neufville 2002; Möller 2008, p. 59). Transfered from the field of stock option valuation, it is a highly appropriate technique to evaluate investment decisions for changeable systems, since any later activation invest for changeability is comparable to the purchase of a stock option (Möller 2008, p. 38). The technique provides a purely economic investment evaluation.

3.2.2.4 Key performance indicators (KPIs)

KPIs are ratio values to quantify target states and to benchmark planned or existing system alternatives of a business operation (Schott 1988, p. 19; VDMA 66412-1, p. 6). They are used for the purposes of design, steering and controlling (Lachnit 1979, pp. 73–83). As steering KPIs, they fulfill a decision support role during the design and evaluation of alternatives (Lelke 2005, p. 11) which makes the choice of relevant KPIs utterly important. In factory planning, KPIs are used to evaluate economic achievements, personnel requirements, area consumption, production characteristics, and the proportion of value adding (Brankamp 2014, p. 34). KPIs describe logistical states in the dimensions of throughput time, performance, and inventory (H-H. Wiendahl 2011, pp. 116–137), count the number of necessary production resources, and put them in relation to the logistical states in terms of productivity. KPIs are often related to forms of waste, as defined by lean production (Ohno 2013, p. 46; Takeda 2006, p. 154). Common production KPIs are listed in Table B.3 (Appendix B). Simulation has proven a helpful tool to measure KPIs because it maps a dynamic process into an experimental model (H-P. Wiendahl 2014, p. 9.29).

There is the potential of misunderstanding by syntax or semantics when KPIs are calculated or interpreted differently by various stakeholders (Lelke 2005, p. 18). Furthermore, the quality of a KPI strongly depends on its actuality (Siegwart 1998, pp. 23–24; Meyer 1994, pp. 43–44). Usually, it is not possible to satisfy analytical requirements with only one KPI. A KPI system relates dependent KPIs in a purpose-oriented manner so that they complement or explain each other (Siegwart 1998, p. 47; Reichmann et al. 1976, p. 45).

3.3 Conclusion of the state of the art

Research works on the design of changeable production systems have achieved much for the transition to flexible and transformable mass customization factories, but none of them alters the classical organizational structure of the coupled production line. Accordingly, they are not fully suitable for the design of personalized production systems. Only the existing concepts and design methods for modular production systems with a flexible material flow have the potential to meet the requirements of a competitive personalized production system (Section 1.1). This section compares these concepts (Table 3.3) and draws a conclusion on research needs.

BMS and their on-demand matching of otherwise line-less production resources delivers the necessary reconfigurability of a system. But the constant movement of structural elements creates rather complex systems. With its technical focus on matching technologies, no holistic design methods or system design guidelines have been developed. The same applies to HMS which were realized on the level of technical production resources only.

The research works on RMS with a design focus on configuring a modular setup on the production system level are very interesting for the design of personalized production systems. Particularly, the works of Koren et al. are suitable, as they attempt to design their production systems for individualized products. Existing RMS design approaches put little to no focus on assembly processes. The configuration on an RMS foresees multiple similar machines per production stages and is, essentially, capacity-based. None of the researches offer a solution for a functional segmentation if product-variety is so high that not only one type of machine can be utilized per process step.

The works of Greschke and W. Kern et al. are closest to the problem statement and research question of this thesis. Both develop a design method for production systems with a focus on the capability to efficiently cope with assembly time variation between different product variants. Both have an exclusive focus on the automotive industry and only consider assembly processes. In the consequence, none of the hitherto existing publications on matrix production system design consider manufacturing processes which are needed for the individualization of product components. Due to the product architecture-driven and capacity-driven design approaches with which W. Kern et al. and Greschke assign production operations to different stations of the system, the functional segmentation of the designed systems are tailored to specific product architectures and SOO. Production systems designed by these approaches must be redesigned if the product architecture of the variant spectrum changes fundamentally. Fundamental changes of product architectures are likely for different product generations of machine modules. A process-driven identification of similar production operations to make the system flexible towards product architecture-related changes of the SOO is not part of W. Kern et al.'s and Greschke's methods. Furthermore, W. Kern et al. and Greschke do not provide for a process-driven identification of specific operations, that require high utilization of e.g. related high-investment or automated equipment and should thus be separated from other operations on functionally specialized process modules.

For the comparison of system design solutions during the design process, value-quantifying approaches are either too cumbersome or rely on a purely subjective evaluation. Using the classical capital budgeting techniques the payback period calculation is not suitable for the evaluation of reconfigurable systems, as it does not consider staggered investments over time. The conventional net present value method, the life cycle costing and investment calculations, as well as the real options analysis have successfully been applied to evaluate changeable production system design embodiments from an economic perspective. However, a purely monetary evaluation hardly makes the system's logistical performance transparent. A KPI system may be applied for the evaluation of logistical system performance as well as for the evaluation of economic feasibility through the integration of investment and

○ not fulfilled
◑ partially fulfilled
● fully fulfilled

			BMS	HMS	RMS							Matrix						**This dissertation**
			Ueda et al.		Pouget	Koren et al.	ElMaraghy et al.	Matt	Colledani et al.	Drabow	Greschke	W. Kern et al.	Fechter et al.	Popp	Bochmann et al.	Göppert et al.	
Scope of system design	Level	Production System	●	○	○	●	●	●	●	●	●	●	●	●	●	●	●
		Cell, Station	○	●	●	○	○	○	○	●	●	●	●	○	○	○	●
	Concept	Elements	◑	◑	◑	●	●	●	◑	◑	●	●	◑	◑	◑	●	●
		Functions	○	●	●	◑	●	●	○	●	◑	●	●	○	●	●	●
		Relations	●	◑	○	●	●	●	◑	◑	●	●	◑	○	●	●	●
	Processes	Assembly	●	◑	●	○	◑	●	○	○	●	●	●	○	◑	◑	●
		Manufacturing	●	◑	●	●	●	○	○	●	○	○	○	○	○	○	◑
		Material Flow	◑	○	○	◑	◑	○	●	◑	●	●	○	●	◑	●	●
	Market	Individualized Product	◑	○	◑	●	◑	○	◑	◑	◑	◑	●	●	○	○	●
		Mechatronic Modules	◑	○	●	◑	◑	●	◑	●	◑	●	●	●	◑	●	●
		High Volumes	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Solution approach	System	Modular	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
		Flexible Material Flow	●	○	○	●	●	○	●	◑	●	●	●	●	●	●	●
	Method	Process-driven Design	◑	○	○	○	○	○	○	◑	○	○	○	○	○	○	●
		Product-driven Design	○	○	○	◑	○	◑	○	○	○	●	●	○	○	○	○
		Capacity-driven Design	○	○	○	◑	○	○	○	○	●	○	○	○	○	○	○
		Design Evaluation	◑	○	◑	◑	○	○	●	●	●	●	○	○	○	○	●

Table 3.3: Distinction of this research work from the relevant state of the art

efficiency KPIs. If KPIs are dynamic and predictive regarding their future values, scenarios can be built, and material flow simulation are applicable as an analytical tool for KPI calculation.

The comparison of design method requirements and available solutions shows that the current state of the art of science and technology does not offer sufficient methods to design and evaluate production system for personalized production. This dissertation attempts to eliminate this deficit.

4 Methodical system

To start the development of the methodical design system of this dissertation, its components must be defined and structured (Section 4.1). To do so, fundamental theories of methods and modeling are introduced and a suitable systems engineering method as well as business modeling notations are chosen in this chapter (Section 4.2). The chapter ends with the introduction of the setup of the methodical system (Section 4.3).

4.1 Components of a methodical design system

A methodical system is defined as a subject-specific collection of adequate methods that ensure effective work and high-quality results. It serves as an input into a method-consciously executed problem solving process. Methods must be invariably valid for a certain class of processes and also satisfy the ceteris paribus clause[90]. (J. Müller 1990, pp. 16–17)

Within the context of this dissertation, problem solving is associated with decision making for the purpose of production system design. To ensure the validity of methods in production system design it is necessary to verify whether a design method is tailored to sufficiently similar requirements and conditions of a prevalent design use case. Moreover, processes and underlying concepts need to be made transparent for a system designer who applies a method. Consequently, verification and the design process itself are only possible with an abstract and simplified description of reality. The use of respective models reduces a production system's complexity (Patzak 1982, p. 307; Holzmüller et al. 2010, p. VII).

Technical (digital) tools support problem solving processes in engineering (J. Müller 1990, p. 16). Tools are part of an effective methodical system, because they make models accessible for application and manipulation, thus enabling the implementation of methods.

All in all, a methodical system is a system of *models*, *methods*, and *tools*, governed by a superimposed *(decision making) process*[91].

[90]Ceteris paribus represents the assumption of constant variables, except the one under immediate analysis (Thommen 2017): There must be an invariable set of attributes existent, which belong to certain classes of problem situations, i.e., to classes of theoretical objects and processes (J. Müller 1990, p. 17).

[91]Laufenberg (1996, p. 6) compiles his methodical system from methods, models and support means. Ehrlenspiel et al. (2013, p. 146) define models, methods, strategies, tools and support means as components of a methodical system. Tools are introduced as processing methods. Support means are

4.1.1 Model

A model is a representation of reality which enables scientific and technical description and analysis of the imaged objects (Gessmann 2009, p. 496). Complex matters of reality are to be made comprehensible and accessible (Holzmüller et al. 2010, p. VII), especially when a manipulation of the real system is not possible for physical-technical, economical or ethical reasons (Patzak 1982, p. 308). A model is a system[92] itself, with its design influenced by prevailing considerations of the systems theory, the empirical know-how of the modeler, and the formal modeling language (Ropohl 2009, pp. 84–88).

Stachowiak (1973, pp. 131–133) defines in his general model theory three distinctive features of a model: representation, simplification, and pragmatism[93]. *Representation* is concerned with the already mentioned mapping of a natural or artificial original, including the allocation of attributes from reality to the attributes of the model. Through *simplification*, only selected attributes of an object that are defined to be relevant are included in its model. *Pragmatism* guides the selection of attributes so that models substitute a modeled object in certain functions, with limited operations, for a certain purpose, for a specific user within a certain time interval.

In summary, a model maps a certain part of reality that is understood as a system, with a representation expressed by a formal modeling notation, in a simplified, abstract, or idealized manner. It allows the examination of precisely this part of reality, scientifically or technically, in order to achieve an objective pursued in reality.

In line with Stachowiak, Patzak (1982, pp. 309–310) formulates five general characteristics for a good model: It needs to be *empirically correct*, *formally consistent*, *useful*, *practicable*, and *parsimonious*. Empirical correctness represents the need for the model to behave in ways that are similar to the represented real system. A model is formally correct if it is consistent in itself. It is useful, if it is built with a certain purpose and delivers useful answers in form and content. Models are finally perceived to be practicable and parsimonious, if they are easy to use and interpret and if the effort to create and apply the model itself is relatively small.

Models are often classified by their purpose[94]: Descriptive models are only intended for a structured presentation of elements and relations within the modeled system. Explanation

described as physical objects for information processing. This thesis subsumes all physical and IT support means under the term "tool".

[92]According to Ropohl's understanding of the term, a *system* is never the actual part of reality but always only a model of reality, as it is described by humans (Ropohl 2009, p. 87).

[93]In the German original they are called "Abbildungsmerkmal", "Verkürzungsmerkmal" and "Pragmatisches Merkmal" (Stachowiak 1973, p. 131).

[94]Töllner et al. (2010, p. 7) state that an objective of a model is a future target state, while a purpose of a model is the reason for a planned action: A "purpose is a target, that is realized by planned actions."

and prediction[95] models are supposed to contribute to the understanding of a system. Decision models are built to support problem solving. (Jokisch et al. 2010, pp. 31–32)

Models are further classified by the type of information given and their concept of abstraction (Scholl 2008, pp. 36–37): Quantitative models supply information purely by mathematical expression, while qualitative models contain (additional) verbal problem descriptions (Jokisch et al. 2010, p. 38). The concept of abstraction influences the validity of a model in terms of value characteristics (stochastic or deterministic model), dynamic behavior (static or dynamic model) and extent (partial or overall model) (Jokisch et al. 2010, p. 38). Independent of its classification, a model is called a reference model, if it is built in a manner to be re-used for the creation of further models (Fettke et al. 2016).

A decision for a suitable type of model for this dissertation project is taken together with the selection of an appropriate modeling notation, relative to requirements of the model (Section 4.2).

4.1.2 Method and tools

The term method is formed by the ancient Greek *metá* (after) and *hodos* (path). It originally meant a systematic mathematic description (Gessmann 2009, p. 489). Nowadays, it stands for a rule-based procedure intended to obtain scientific knowledge or practical results (Duden 2017).

A method determines a process to reach a certain target and ensures the acceptance of the results through specified conditions of validity (J. Müller 1990, p. 17). It can be of algorithmic or heuristic nature (J. Müller 1990, p. 22). An algorithmic method comes up reliably with a desired result after a finite number of operations or terminates with justification (Klaus 1968)[96]. It needs a thorough understanding of the entire system, including the interaction between its components, and it is often tailored to very specific situations and not suitable to address complex problems of a higher conceptual level (Suh 2001, p. 10). Heuristic methods do not guarantee a targeted result but achieve a target-oriented and effective work process (J. Müller 1968; Pushkin 1971) on the basis of general principles and axioms (Suh et al. 1978, p. 127). Heuristic methods are typically employed if problems are too complex to be solved strictly by algorithms; if information is lacking or are only available at a later point in time of the problem solving process, due to stochastic or probabilistic process sequences; if users lack the ability to process algorithmic methods; and if human creativity or expert knowledge is a deliberate input (J. Müller 1990, p. 22).

[95]Simulation and queuing models are a special form of prediction models (Scholl 2008, pp. 36–37).
[96]cited after Müller (J. Müller, p. 22)

Methods build models during their execution, in order to document results and make them accessible for further analysis and subsequent steps of a design process. Methods are often tied to certain modeling notations that they recommend for the documentation.

Tools are conventional or information-technology working appliances. They are necessary to apply or manipulate models, or to enable a more efficient, method-based, problem solving process. Müller (J. Müller, p. 16) names AI and computer science as examples. The necessity for and the type of required tools are determined by the applied methods.

A decision regarding the nature of methods and the type of tools for this dissertation project is taken together with the selection of an appropriate general design method, relative to the requirements of the design method (Section 4.2).

4.1.3 Decision making in design processes

Design has historically been defined as the conception and realization of new things (Simon 1996, p. 111; Cross 2006, p. 1). It involves two distinct types of action (Suh 1984, p. 397):

1. creative problem solving, to come up with design solutions
2. analysis, to determine if a proposed solution is correct or rational

The complementary analysis ensures the quality of a design, as it helps to assess and evaluate a design decision and facilitates a structured decision process among different solution ideas.

Decision making is a focal point of a design method. The quality of the superimposed decision process itself is of utmost importance to the quality of a design (Suh 1984, p. 398). Decision-making processes are commonly divided into five phases of *initiation*, *consideration of alternatives*, *decision on alternatives*, *implementation*, and *review* (E. Heinen 1971, p. 31). E. Heinen (1971, p. 22-28) outlines four elements specifically for the evaluation of alternatives during the design of (economic) systems: In his decision-theory approach, business economic *objectives* are defined as the basis of a decision process, to describe requirements, and to be used as evaluation criterion for the selection of alternatives. General *decision factors* serve in the systematization of alternatives. Normative *explanation* and *decision models* are important elements to understand an outcome and to allow for a logical derivation of different alternatives through a formal (axiomatic) description of the decision problem.

For the development of the methodical design system follows that all five phases of decision-making, named above, need to be embedded in a systematic design process. Furthermore, the methodical design system should support decision making by incorporating the four elements for the evaluation of alternatives, also named above. Specific requirements for the decision making and the design process are derived in the requirements of the design method (Section 4.2.1).

4.2 Selection of a general design method and an appropriate modeling notation

The overall scope of this thesis intends to foster the design of matrix production systems. Production systems are non-trivial, socio-technical subsystems of an enterprise (Section 2.1.3). There is a large number of general approaches for the systematic design of technical systems and numerous enterprise modeling techniques[97]. Design methods are commonly separated into plan-driven versus agile design methods (Boehm et al. 2004, pp. 25–57). Agile methods focus on project organization and management (Braun 2013, pp. 53, 59). They do not give structure to the design process itself, which makes them inappropriate for the development of a production system design method. Consequently, only plan-driven methods are discussed in the following.

Common plan-driven design methods are listed by Hiersig (1995, p. 634)[98]:

For problem solving:

- Creativity techniques,
- Catalogues, check-lists, model kits,
- Design principles,
- Physical effects analysis,
- Morphological technique.

For the evaluation of design solutions:

- (Weighted) score evaluation,
- Technical-economical valuation,
- Value benefit scoring model.

The separating of problem solving from the analysis and evaluation of design solutions into independent methods bears the risk that solution alternatives are collected without consideration of mutual interdependencies. As a result, the design may contain contradictory sub-functions which have to be solved by iterations. Holistic approaches combine problem solving and the evaluation methods. They are associated to the fields of **systems engineering**, **value engineering** and **product development**[99] (Pahl et al. 2007, pp. 17–22).

Value engineering methods are made for the reengineering of products with the objective to improve value and reduce cost (Pahl et al. 2007, p. 19; DIN EN 12973, p. 25). **Systems engineering** is an interdisciplinary field of science that provides a philosophy, methods, and techniques for a holistic analysis and engineering of complex

[97] Pahl et al. (2007, pp. 23–28) give a comprehensive overview over product and system development methods, that have been published by 88 different authors since 1953.

[98] Feldhusen et al. (2013b, pp. 350–380) gives details on creativity techniques. VDI 2222-1 and VDI 2222-2 contain information on catalogues and checklists. The theory of inventive problem solving (TRIZ) is a well-known design approach, based on inventive problem solving. It was developed by Altschuller who derived generic principles by statistical analysis of patterns in patents (Altschuller 1998). For an introduction into physical effects, see Claussen et al. (1998, p. 65). Morphological techniques were first developed by Zwicky (1989). Compare VDI 2225-3 for technical-economical valuation, and Zangemeister (2015) for the value-benefit scoring model.

[99] The German original term for the third field is *Konstruktionsmethoden*.

systems (Haberfellner et al. 2015, p. 31; EIA 632, p. 1). **Product development** focuses specifically on technical design and the development process of technical objects and products (VDI 2221, p. 38).

Value engineering is not tailored for the initial design of a production system and is, therefore, not considered further in this thesis. Systems engineering and product development both define design processes and methods. The defined processes show corresponding activities (Haberfellner et al. 2015, p. 92) and common problem-solving methods are shared (Haberfellner et al. 2015, pp. 83–84; VDI 2221, p. 38). It can thus be concluded that the differentiation of systems engineering and product development is only artificial. A general design method will be selected from these fields for the methodical design system of this thesis.

Considering the multitude of systems engineering and product development methods and modeling notations, a sophisticated choice (Section 4.2.2) is only possible in consideration of requirements (Section 4.2.1). Table 4.2 compares possible methods with all identified requirements.

4.2.1 Requirements for the methodical design system

Due to the interdependency of methods and modeling notations (Section 4.1.2), a general design method and a modeling notation should not be selected separately. The method and the model must be formally compatible. This is ensured if a general design method with an inherent modeling notation is selected. If a general design method does not specify a standardized modeling notation, common standardized modeling notations should be checked with regard to their suitability for a combination with the selected method.

The following sections elaborate specific requirements for the design method and model.

4.2.1.1 Requirements for a general design method

Production system designers often have distinct expert knowledge. It should be possible to utilize this knowledge during the design process and control decisions by expert knowledge. It is also conceivable that not all information about a design use case is known upfront. Consequently, only heuristic methods are further considered for this thesis.

The design method should support a creative and analytical decision making of the system designers (Section 4.1.3), in order to guide the design decisions (Requirement **R1.1**). Hence, it should structure the design process, enable the evaluation of alternative design solutions and provide general decision guidelines.

The method should be requirement-considerate, so that target objectives of the production system design are transparent throughout the entire design process (Requirement

R1.2). There are non-functional requirements, such as production quantities, variant mix, as well as the general requirements for a competitive production system of personalized production, and project-specific, strategic constraints. More important, requirements on the production system arise as functional process requirements through the products to be produced. The method should allow to decompose functional requirements of the production system, and devise design solutions, aligned with the requirements of a production system design project.

4.2.1.2 Requirements for the model

To sufficiently create the production system design embodiment for subsequent implementation, the model needs to reflect the production system by all system theory modeling aspects of functions, objects and processes (Section 2.1.3).

Production system functions correlate to the system's abilities and application ranges. Functions are directly linked to production system elements and their components on subsystem levels. The model should allow an attributive assignment of properties to production system elements on different hierarchical levels. The matrix production system is built by process modules as instanced system element objects[100]. Each process module belongs to a certain process module class. To model the functional system concept of a matrix production system, a *function-object model* is needed, in order to describe the process module classes and their functions (Requirement **R2.1**).

To explain the structural concept of the system, an *object model* (Requirement **R2.2**) of the production system needs to represent the above-mentioned process modules as elements of the production system, define their multiplicity, and show the relations between them. To make sure that no conflicting design solutions manifest in the system design, the object model should contain a top-down system decomposition and show couplings among structural elements.

The function-object model and the object model generate the fundamental organizational structure of the system. A *process-object model* is, furthermore, needed to describe the dynamic system behavior during operation (Requirement **R2.3**). It illustrates the dynamic relationship pattern and the interaction of process modules during operation. The process-object model should make the impact of the product architecture on the production system visible, which alters the system control command (SCC), i.e. the order of execution of a system's process modules.

[100] An *instance* is a specimen of a class. *Object* and *instance* are synonymous. (Balzert 1999, pp. 541, 545)

4.2.2 Discussion of methods and modeling notations

Specker (2005, pp. 39–45) suggests to use the system modeling aspects of process, function, object, and task to classify modeling techniques for systems engineering. It is possible to allocate common systems engineering and product development design methods and their associated modeling notations and diagrams, as well as common enterprise modeling notations, into a matrix of these modeling aspects (Table 4.1).

prim. / sec.	Process	Function	Object	Task
Process	- IDEF2 - ARIS Business Model **Process Model** ARIS | IDEF	- ARIS Function Sequence ARIS	- UML State Machine - SysML State Diagram - IDEF3 Object State Transition Diagram - IDEF4 State Diagram IDEF | UML | SysML	- Task-oriented information flow
Function	- UML Activity Diagr. - SysML Activity Diagr. - IDEF3 Process Flow - EPK(ARIS) - PAP DIN66001 - Petri Net - FFBD, EFFBD - SA/SD Dataflow Diagr. ARIS | IDEF | UML | SysML	- IDEF0 - ARIS Functions Structure* - Functions Structure Diagram* **Functions Model** ARIS | IDEF | VDI 2221	- IDEF4 Client/Server Diagram - UML* Class Diagram - SysML Block definition Diagram IDEF | UML | SysML	
Object	- UML Sequence Diagr. - UML Timing Diagr. - UML Interaction Overview - SysML Sequence Diagram - AD Flow Diagram - Precedence Graph* - Precedence Matrix* UML | SysML | AD	- IDEF4 Behavior Diagr. - AD FR/DP/PV Hierarchies* - Function Effect Structure IDEF | AD | VDI 2221	- UML* Class, Object, Package, Composite Structure, Profile & Component Diagram - SysML Block definition, Package, Internal Block Requirement, Parametric Diagram - AD Module Junction Diagram* - Module Structure* - IDEF4 Class Inheritance, Relation, Link & Instance Link Diagram - IDEF1x* - Express/ExpressG* - ARIS ERM - BOM* - ER/EER - Variant-Tree* **Objects Model** ARIS | IDEF | UML | SysML | AD | VDI 2221	
Task	- Workflow Diagram - BPMN - UML & SysML Activity Diagram (with responsibilities) - Value Stream Mapping - Value Stream Design UML | SysML	- UML/SysML Use-Case Diagr. - ARIS Functions, Organizations Diagr. - SA/SD Context Diagram ARIS | UML | SysML	- UML Communication Diagram UML	- Organizational Model - ARIS Organizational Structure **Organization Model** ARIS

*Notation applicable for product modeling

Table 4.1: Specker (2005, p. 40) modeling matrix, filled with common notations & diagrams

To fulfill the requirements of an function-object (R2.1), object (R2.2.), and process-object model (R2.3) it is necessary to model the system by more than two modeling aspects. Independent object and functions models, such as Chen's (1976) (enhanced) Entity Relationship Diagram (ER, EER) (Bagui 2005) or the Functions Structure Diagram (Specker 2005, p. 82), cannot fulfill the requirement for process modeling. The same exclusion applies to Express and its graphical subset Express-G (ISO 10303-11), a product-information model notation that was developed to facilitate the computer-interpretable product model data exchange standard STEP (H-P. Wiendahl 2010, p. 155). Business process modeling notations, on the other hand, often lack an object focus. Flow diagrams such as the FFBD and eFFBD (NASA 2007, pp. 52–54, 285–288) or the data flow diagram of SA/SD (Ross et al. 1977; FitzGerald et al. 1987) display a system's behavior by illustrating the functions of the system. A Program Workflow Diagram (PAP) such as defined by DIN 66001 shows a functions-oriented graphical flow of operations to execute an algorithm. Petri nets (Petri 1962) model states and transition stages of a system to describe its behavior. BPMN (OMG BPMN) and lean production Value Stream Design (Erlach 2020; Rother et al. 2009) both model the organizational and process structures of a production system. They are task-oriented and use-case specific, which makes them inappropriate for a reference production system model.

Instead of independent notations, integrated techniques offer a consistent combination of methods, notations and diagrams for a holistic description of systems by several aspects. Established integrated techniques with a focus on modeling are the modeling framework ARIS and the modeling language families of UML, SysML and IDEF. Established integrated techniques with a focus on methodical design are the MTO analysis, the product development procedures MVM and iPeM, the systems engineering guidelines VDI 2221 and INCOSE, and the systems engineering design methodology of Axiomatic Design (AD) for Systems.

ARIS is an information modeling framework to model business processes (Scheer 1998a; Scheer 1998b). Processes are described functions-oriented, as EPK. Even though it contains an ER object model, it is essentially only a data modeling method (Specker 2005, p. 74). As such, it cannot fulfill the requirements of production system modeling and will not be considered further.

UML (ISO/IEC 19505-1; ISO/IEC 19505-2) was developed to allow analysis, design, and implementation of software-based systems and business processes (OMG UML 2.5 01/21/2021, p. 1). It constitutes a great number of different diagrams, in order to model a system's structure and its behavior in various ways (OMG UML 2.5 01/21/2021, pp. 691, 695). UML is widely used, but it has a strong software bias.

SysML is an UML dialect, which was created for systems engineering (OMG SysML 1.4 10/04/2017, p. 1). Overall, it constitutes a smaller number of diagrams[101] than UML and is more focused on the needs of non-IT systems.

IDEF ranges from functional modeling (IDEF0) to information modeling (IDEF1, IDEF1x) and process modeling (IDEF2, IDEF3) to object-oriented modeling (IDEF4) (KBSI 1992; KBSI 2021). It originates in Computer-Aided Manufacturing (CAM) (Noran 2004, p. 1).

Due to their holistic system focus, **UML**[102], **IDEF** and **SysML** are all potential modeling techniques to be applied for production system design (Table 4.2). Their multiple diagrams implicitly deliver a guideline on how to create a holistic system model. However, with their focus on modeling, they all lack a procedural description of a design process to guide good design decisions.

The integrated techniques with a focus on methodical design deliver such procedural models.

The **MTO analysis** (Strohm et al. 2012) is mainly a procedural guide for the analysis and evaluation of business enterprises (Ulich 2013, pp. 6–10). However, it only supports a task-oriented process model (Specker 2005, pp. 127–132). As such, it cannot fulfill the requirements of production system modeling sufficiently and will not be considered further.

MVM (Lindemann 2007) and the concept of **iPeM** (Albers et al. 2003; Albers et al. 2004; Albers et al. 2007) are product development methods that understand a design process as a network of activities. Specifically iPeM offers a comprehensive collection of methods, organized in an activity matrix (Meboldt 2008, p. 169; Albers 2010, p. 353). It contains a problem-solving process description (Albers et al. 2003) and a (however unguided) decomposition approach, in order to translate a system of objectives into a system of objects (Albers et al. 2011, p. 1). Both concepts have only been applied in product development. Although they contain systematic problem solving, they don't deliver general decision-making principles.

The design guideline **VDI 2221**, commonly applied in Germany, defines a design process that incorporates numerous plan-driven, independent design methods[103]. The

[101]SysML adds to the diagram types of UML a requirement diagram for verification & validation of system requirements and a parametric diagram to show parametric constraints among structural elements. The software-development-centric component, deployment, and profile UML diagrams are not part of SysML. All alternative variants to the sequence diagram from the interaction diagram package are considered redundant and are also not part of the SysML. (OMG SysML 1.4 10/04/2017, p. 187)

[102]UML and SysML do not offer a function-object model. The object-function class- and block-definition diagrams could be applied instead.

[103]Included, amongst others, are the methods of Andreasen et al. (1987), Ehrlenspiel (1985), Hubka et al. (1988), Lindemann (1980), and Pugh (1990) and J. Müller 1990 (all cited from VDI2221). In total, the guideline cites 24 of the 88 authors listed by Pahl et al. (2007, pp. 23–28) (compare Footnote 97).

○ not fulfilled ◑ partially fulfilled ● fully fulfilled		AD for Systems	IDEF family	SysML	UML
Method	**R1.1 - guide design decisions**				
	structured design process	●	○	○	○
	evaluation of alternative design solutions	●	○	○	○
	general decision guidelines	●	○	○	○
	R1.2 - requirement considerate				
	consideration of system constaints	●	◑	●	◑
	comparison of funct. req. and system abilites	●	○	○	○
Model	**R2.1 - function-object model**				
	functional system abilities	●	●	●	●
	different system hierarchy levels	●	◑	◑	◑
	R2.2 - object model				
	classification of process modules	●	●	●	●
	multiplicity of process modules	○	●	●	●
	relation of process modules	●	●	●	●
	show couplings of structural elements	●	◑	●	◑
	R2.3 - process-object model				
	operational system behavior	●	●	●	●
	impact of product architecture on SCC	●	◑	◑	◑

Table 4.2: Comparison of method and model requirements & integrated system design techniques

design process of VDI 2221 is split into the sequential phases[104] of design goal clarification, functional structuring, generation of solution ideas, system decomposition, design of modules, system composition, and documentation (VDI 2221, p. 9; Braun 2013, p. 48). A combination of VDI 2221 with the V-Model procedure of VDI 2206 (p. 29) allows for a continuous comparison of design requirements and solutions (Feldhusen et al. 2013a, p. 20). However, the comparison is only supplied during the phase of system integration. Neither does the V-model procedure contain specified guidelines on how to execute the decomposition of system functions (Puik 2017, p. 46), nor does VDI 2221 itself. Suggested methods to develop and evaluate solution ideas (VDI 2221, pp. 34–38), but non of the methods delivers an approach to compare different solutions for best suitability. Specifically, VDI 2221 does not contain a strategy on how to handle conflicting subsystems.

The **INCOSE** (INCOSE 2015) guideline is a compilation of standards and methods for all system-engineering phases, from concept definition to service life management. It contains sequential, evolutionary concurrent, as well as interpersonal, unconstrained (agile) concepts. The related standard EIA 632 is the counterpart of the above-introduced VDI

[104]The guideline is under revision: Its subsequent versions VDI 2221-1 and VDI 2221-2 (available as drafts only) incorporate simultaneous and concurrent engineering.

2221. It is also a primarily sequential process with iterations, modeled as a top-down development and bottom-up realization V-model (INCOSE 2015, pp. 29–32; EIA 632, pp. 58–59). Similar to VDI 2221, the guideline suggests methods to find solutions of design problems, but does not contain a systematic comparison of selected design solutions of different system modules. The risk of an intensive iteration process, to resolve contradictory design solutions, exists here as well.

Neither of the integrated methodical design techniques, hitherto described, deliver a modeling notation for the documentation of system design results, or a decision model to decide on a good design by a comparative evaluation of different design solutions. VDI 2221 specifies modeling aspects, with which results are to be documented for each phase of the design process, but does not specify a specific modeling notation either. **MVM**, **iPeM**, **VDI 2221** and **INCOSE** will thus not be considered further.

Axiomatic Design (AD) and its system engineering specification **AD for Systems** has been developed by Suh (2001, 1990, 1984) et al. (1978) to guide the design process of complex technical systems. AD for systems specifies both a procedural model of the design process as well as a notation for the documentation of the process. AD is based on three core principles:

1. a strong alignment to the customer needs (Suh 2001, p. 3)
2. a very structured approach to hierarchically decompose the design problem to achieve functional separation of design solutions (Suh 2001, p. 21)
3. an axiomatic definition of criteria to judge the quality of a design solution, in order to help a designer concentrate on promising, ”good-design“ ideas (Suh 2001, pp. 9–10)

AD allows to construct systems from modules but ensures a top-down approach to design the system framework first (Suh 2001, p. 195). A systematic for mutual comparison of independent design solutions to identify conflicting solutions in the system synthesis is also contained in the method (Suh 2001, pp. 16–19).

The consistent customer-orientation and the systematic to identify conflicting design solutions distinguishes AD from all other general system design methods introduced above. AD supports heuristic design with an axiomatic design process (normative decision theory), and it includes the evaluation of different design solutions, as well as the consideration of design constraints (Design constraints (C)).

AD for Systems expands the systems design methodolgy of AD. The tree and design matrix representations of the decomposition hierarchies in AD (Section 4.2.3) already constitute a function-object system model across different system levels. AD for Systems adds the *Module Junction Diagram* to model the system structure as an object model, and a *Flow Diagram* to model the system relations as a process-object model[105].

[105]Notations and diagrams of AD for Systems are explained in detail by Suh (1998) and Suh (2001).

AD for Systems is well suited to fulfill the requirements of the general design method and modeling notation (Table 4.2). It is selected as the general design method and modeling notation for the methodical design system, developed by this dissertation, for several critical reasons:

- its integrated methodical and modeling approach
- its representation of different system levels in hierarchies
- its transparent representation of the mapping of requirements and design solutions
- it offers specific guidance for good design

AD lacks the possibility to express multiplicity of object instances. To compensate for this deficiency, the **specification of multiplicity** will be borrowed from the **UML** notation. AD offers an excellent way to compare product-related functional requirements on the production system with a product system's functional capabilities. A process view description of the product in relation to the product system also seems possible. For the thereby necessary analysis of the product architecture, the precedence graph is an appropriate model[106]. It maps assembly tasks as nodes in a graph, where the edges between those nodes represent the sequence relation of the assembly tasks and give the degrees of freedom in assembly execution (Ammer et al. 1986, p. 94).

The following section provides a more detailed introduction of AD.

4.2.3 Axiomatic Design (AD)

AD guides the design process through four domains of the design world (Figure 4.1). Each domain is characterized by its respective design vector. CA is the vector of the customer domain. It holds the customer attributes of the system which are a structured collection of customer needs. FR is the vector of the functional domain. It holds the functional requirements of the design, transforming the customer needs from the customer domain into a set of independent design goals. DP and PV contain the solution parameters of their respective domains. They are called design parameters in the physical domain and process variables in the process domain. The design process proceeds from collocated domain pair to collocated domain pair, mapping FR to CA, DP to FR, and finally PV to DP. Each mapping ends up in a design vector that ultimately becomes the input of the next mapping. This means:

- The left domain of the pair holds the requirements, representing the design goals.
- The right domain represents the appropriate design solutions.

[106] The precedence graph transfers the object-oriented, physical component-structure model of a Bill of Materials (BOM) which lists parts and assemblies of a product (Eversheim et al. 2014, p. 7.46) into a process view. This is more appropriate to display the assembly's operational behavior. To allow for improved computational processing the precedence graph may be saved as a matrix or relational table (Zeile 1995, p. 20).

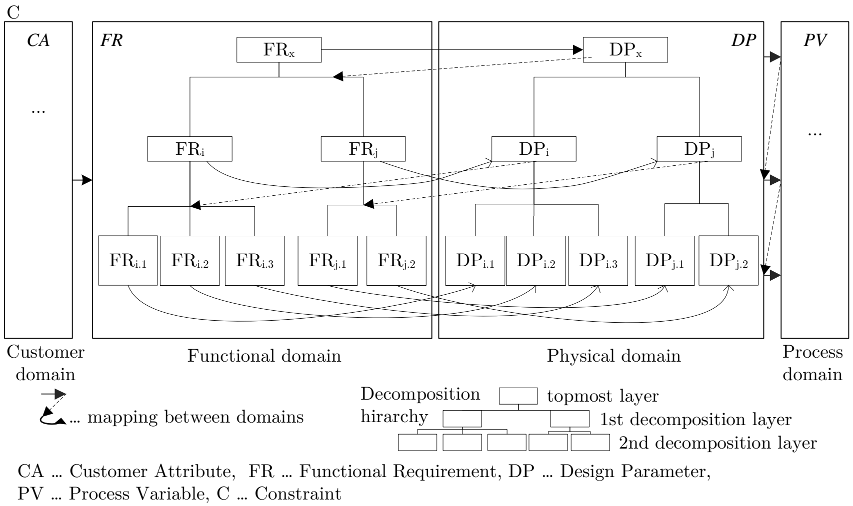


Figure 4.1: Four domains of Axiomatic Design (AD) and exemplary graphical notation of *FR-DP* hierarchies, according to Suh (2001, pp. 11, 30)

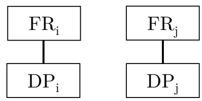
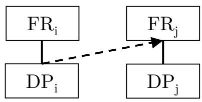
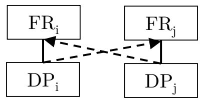
- Any mapping between domains must be finished completely before proceeding to the next domain pair.
- The customer needs are apparent throughout the complete design process, as they are passed onto the next domain with each mapping.

The solution space is built up layer by layer in each design domain. The set of requirements for each subsequent layer derives directly from the succeeding domain's chosen upper-layer solution parameter (Figure 4.1). Through this decomposition every solution parameter ultimately fits the upper-layer parameter it depends upon.

Higher-layer design solutions act as system constraints on all its subordinate layers. In addition to the system constraints which originate from the decomposition process, superordinate requirements called input constraints set boundaries to the possible space of acceptable solutions (Suh 2001, p. 14). Quality, cost, and production rate are often treated as design constraints. Usually, the system design needs to be completed before it can be checked regarding its constraints.

AD provides two fundamental axioms (Suh 2001, p. 16):

- **Independence Axiom (Axiom 1)**: *Maintain the independence of the FRs.*
- **Information Axiom (Axiom 2)**: *Minimize the information content I of the design.*

	Uncoupled design	Decoupled design	Coupled design
Mathematical representation	$\begin{Bmatrix} FR_i \\ FR_j \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \bullet \begin{Bmatrix} DP_i \\ DP_j \end{Bmatrix}$	$\begin{Bmatrix} FR_i \\ FR_j \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \bullet \begin{Bmatrix} DP_i \\ DP_j \end{Bmatrix}$	$\begin{Bmatrix} FR_i \\ FR_j \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \bullet \begin{Bmatrix} DP_i \\ DP_j \end{Bmatrix}$
Graphical representation			

FR ... Functional Requirement; DP ... Design Parameter

⟶ Direct FR-DP mapping (uncoupled) - - ➔ Further FR-DP mapping (decoupled, coupled)

Figure 4.2: Mathematical and graphical representation of uncoupled, decoupled, and coupled designs (Suh 1984, p. 401) (representation adopted from Linck (2001, p. 57)).

Axiom 1 forces the designer to map an individual solution parameter to each separate requirement (Suh 2001, pp. 18–29). Moreover, its goal is to keep design solutions independent of each other. Ideally, each design solution only influences exactly one independent design requirement in order to realize functional separation. Designers are forced to check each chosen design solution against all other same-layer solutions parameters. Thus, a solution space designed with AD does not contain conflicting solutions to different requirements of one system.

As an alternative to the graphic tree representation of the decomposition (Figure 4.1) which may become confusing for large systems there is a mathematical notation to represent the mapping result (Figure 4.2). In the mathematical notation, the two design vectors of the mapped domains are related through the product design matrix $\left[A\right]$ and the process design matrix $\left[B\right]$ (Suh 2001, p. 18):

$$FR = \left[A\right] DP \qquad DP = \left[B\right] PV \tag{4.1}$$

Each design matrix represents one decomposition layer of the mapping process. In the case of a linear design, it is common practice to replace the matrix elements A_{ij}, B_{ij} (where i_{max}=m, j_{max}=n and $i, j, n, m \in \mathbb{N}$) by an "$x$". (Suh 2001, p. 19)

The form of the matrix is defined by the type of dependency between requirements and solution parameters. In the case of an ideal design, each decomposed requirement is only influenced by exactly one independent solution parameter. The ideal design matrix is a diagonal matrix (Figure 4.2, left). A triangular design matrix indicates a decoupled design (Figure 4.2, middle) which AD promotes as a second-best solution if an ideal design cannot be achieved. In a decoupled design, there are design solution parameters that influence several design goals. However, a stable system can be reached if the solution parameters are implemented in a certain order. A coupled design, on the contrary, contains feedback loops between the parameters. It is impossible to reach a stable system state, as the change of a design solution parameters cause an unintended influence on other parameters (Figure 4.2, right).

Both a diagonal and a triangular design matrix satisfy Axiom 1. If the design matrix is neither diagonal nor triangular, the design is coupled and does not satisfy Axiom 1. (Suh 2001, p. 19)

In the case of an ideal design, the number of requirement and solution parameters must match exactly. The ideal design matrix has a square matrix shape. If there is an unequal number of design goals and solutions parameter to be mapped, it is either a decoupled redundant or a coupled design. A redundant design may fulfill Axiom 1, if the design solution parameters outnumber the design goals (i.e. $|DP| > |FR|$) and the order of solution parameters can be varied to reach a stable system state. (Suh 2001, pp. 22–23)

Special focus must be put on the translation of CA into independent FR_i as a prerequisite for independence in the subsequent design solutions. FR_i must be collectively exhaustive and mutually exclusive (CEME) (C. Brown 2005, p. 189).

To identify dependencies between design domains, Linck (2001, p. 59) introduces two questions:

1. *Does the realization of DP_j affect the achievement of FR_i?*
2. *Would failing to implement DP_j affect the system's ability to achieve FR_i?*

For the design of flexible systems, Suh (2001, p. 203) suggests building up a knowledge base of design solutions (Equation 4.2). The \$ symbol indicates that all DP_i are conceived as solution candidates to satisfy the respective FR_i.

$$
\begin{aligned}
&FR_1\$(DP_1^a, DP_1^b, ..., DP_1^t)\\
&FR_2\$(DP_2^a, DP_2^b, ..., DP_2^q)\\
&\qquad\qquad ...\\
&FR_m\$(DP_m^a, DP_m^b, ..., DP_m^s), \quad a...t \in \mathbb{N}
\end{aligned}
\tag{4.2}
$$

Axiom 2 delivers a decision-making principle. It helps to select a design parameter from different options which fulfill Axiom 1 equally well (e.g. all options result in an independent design). Axiom 2 evaluates the probability of a design parameter to successfully satisfy its requirement. The best design is considered the one with the least information content (I). I is calculated for one pairing of design requirement and solution parameter as the logarithm of the inverse of the success probability (p_i) of a design, $i \in \mathbb{N}$ (Equation 4.3)[107]. The smallest achievable I equals zero for $p = 100\%$. On the contrary, $I \to \infty$ for $p = 0\%$. The

[107]Compare Shannon (1948, p. 80) for the specification of information content as a logarithmic quantity.

information content of a complete system I_{Sys} can only be derived once all the system's I_i are known, as it is calculated as the sum of all I_i (Equation 4.4)[108]. (Suh 2001, pp. 39–40)

$$I_i = log_2\left(\frac{1}{p_i}\right) = -log_2 p_i \tag{4.3}$$

$$I_{Sys} = log_2\left(\frac{1}{p}\right) = -log_2 \prod_{i=1}^{m} p_i = \sum_{i=1}^{m} I_i \tag{4.4}$$

The success probability p of a design depends on the overlap between design range dr and system range sr (Figure 4.3, left). A design range is defined as a specified allowable tolerance of a design solution. A system range specifies the possible range of dispersing solution parameter values. The overlap is referred to as common range cr. The success probability p equals the area A_{cr} under the system probability density function within the common range (Equation 4.5)[109]. (Suh 2001, p. 41)

$$I_i = log_2\left(\frac{1}{A_{cr,i}}\right) = log_2\left(\frac{|sr_i|}{|cr_i|}\right) \tag{4.5}$$

As such, the success probability p evaluates how much of a system range sr is covered by a common range cr. It states how likely it is that a design solution achieves a required tolerance. If $p = 100\%$, all possible samples of the solution parameter are inside the acceptable tolerance zone dr. The complete tolerance band of a design solution parameter fulfills the requirements, so that any outcome of the parameters leads to a stable process. If all values are outside of the design range dr, none of the possible outcomes fulfills the required tolerances. Consequently, $p = 0\%$.

The calculation of the information content I, as defined by Suh (2001, p. 41), is only feasible if the selected design solution values are spread with a probability distribution, i.e. a system range with a range of tolerance. It is not feasible if the design goal is represented by a dispersion of requirements, i.e. a design range with a spread of values. The latter is often the case for the design of flexible systems, as flexibility demands different values for one requirement over time. Helander et al. (2002; 2007) identified the same problem for the axiomatic design of ergonomic systems. They redefine system and design range into *supplied range* and *desired range* and evaluate how much of the desired range (instead of system range) is overlapped by the common range cr of the two ranges, in order to judge the probability of success for a design solution (Figure 4.3 right, and Equation 4.6).

$$I_i \quad (Ergonomics) = log_2\left(\frac{desired \quad range}{common \quad range}\right) \tag{4.6}$$

[108]The simplification of equation 4.4 is only valid for an uncoupled design, with $m \in \mathbb{N}$ independent FR_i.
[109]The transformation of equation 4.5 is only valid for a uniform distribution of parameters.

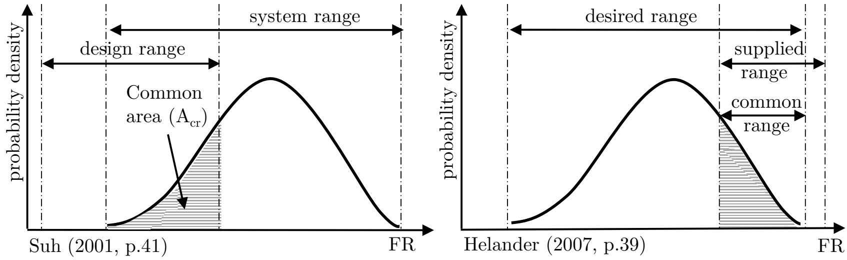


Figure 4.3: Comparison of Information Axiom components as of Suh and Helander

For the design of a flexible system the information content I should be calculated as specified by Suh (2001, p. 41), in order to judge on the tolerance fulfillment of a design solution. The calculation rule of Helander et al. (2007, 2002) needs to be used to assess the flexibility range of a designed system.

Appendix C.1 and C.2 demonstrate the application of the AD axioms with practical examples.

AD has furthermore eight corollaries and many theorems, that are derived from the the axioms. Corollaries and theorems give guideline to the designer on how to achieve a good design (Suh 2001, p. 24). Corollaries are listed in Appendix C.3. Theorems can be found in Suh (2001, pp. 60–64).

AD has been applied in the context of manufacturing system design manifold times. Suh et al. (1978) discuss the general design of manufacturing systems on a high conceptual level and develop relevant axioms and corollaries. Sohlenius (1992) and Vallhagen (1994) enhance the AD domains with an additional domain for process requirements. Rauch (2013) and Rauch et al. (2015) use AD for the design of decentralized production networks. Cochran et al. (1996) compare different manufacturing system setups. Linck (2001) and Cochran et al. (2001-2002) analyze dependencies in lean production methods. Cochran et al. (2000) segments production systems. Matt (2007) identifies general FR and DP of flexible and changeable production systems. Abdelkafi (2008) elaborates on solutions to reduce variety-induced complexity in mass customization production systems. Reichenbach (2010) develops human-robot-collaboration assembly cells by AD decomposition of assembly processes. Al-Zaher (2012) applies AD principles to map product design-driven flexibility into the design of flexible and reconfigurable automotive body-in-white framing production lines. Babic (1999) selects manufacturing machines for FMS out of a knowledge module to satisfy his set of defined FR. Bahadir et al. (2014) compare different robot arms for robotic system design with Axiom 2. Puik (2017) and Puik et al. (2017, 2014, 2013a, 2013b, 2013c) suggest an AD-inspired method to guide the development process of reconfigurable manufacturing systems for microsystems and assess the difficulty of reconfiguration using reconfiguration schemes. They focus on the cell level and direct the concurrent engineering process. Weber (2018) applies AD within a concept of agile product development for the design of assembly system equipment. None of the applications tackle the challenges of personalized production system design. The applications are either only conceptual or they have a very specific focus, such as the development of a robot cell or a specialized production segment. A method for a detailed functional, structural, and hierarchical design of a production system is not delivered.

4.3 Setup of the methodical design system

Different components are needed for the methodical design system (Figure 4.4). A *generic reference model* builds the basis. It models the structural concept of the personalized production system and its elements, i.e. the system's process modules, the relations between the modules, and their interaction with the product during operation.

A heuristic *design method* instantiates the conceptual design of the reference model with a detailed design of a matrix production system's organizational structure in all system theory concepts. The design method follow AD along its four design domains for the *process module design*. The system hierarchy and the system functions are determined by decomposition of needed manufacturing, assembly, and material flow operations. As a result of the process module design, functionally pre-instanced process modules are configured. They are designed to meet general, reference characteristics from the product spectrum of a manufacturer and saved in a knowledge base, to be re-used in subsequent production system design projects.

A design method further provides for an *overall system design* which selects and adapts specific process module configuration as system elements to fit the production program of a particular production system design project. The overall system design instantiates the process modules and relates them in a system layout. The process structure and the material flow of the system are delineated to enable a stable operation and control of the system.

Finally, a *comparative evaluation* is introduced which uses discrete event material flow simulation, in order to estimate dynamic parameters of the production system for the calculation of the KPIs.

The methodical design system reflects the decision theory approach of E. Heinen (1971). The method allows for a systematic design of alternative production system design embodiments and supports the production system designers in their decision making and review of the design. The methodical system embeds E. Heinen's elements for a systematic evaluation of alternatives (Section 4.1.3): *Business economic objectives (1)* are defined as input constraints (Cs), to enable the final decision on one overall system design. Moreover, requirements of the design are derived from general product characteristics and the production program and described as CAs. As *general decision factors (2)* AD axioms and selected AD corollaries are provided in the method. Both, the general process module design as well as the project-specific production system design are checked for independence whenever a solution is mapped to a requirement. As a *normative explanation model (3)* the generic system model outlines the general system theory concept of the matrix production system to be aimed for in the design. Finally, to serve as *decision model (4)*, calculation rules for the evaluation of process capability are taken from AD, and calculation rules for the evaluation of changeability are being developed as part of the process module and system design.

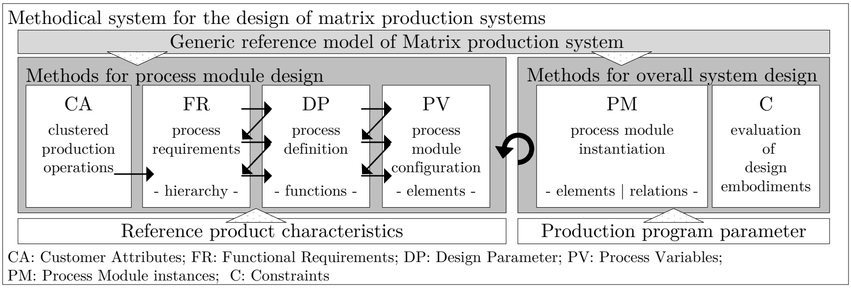


Figure 4.4: Setup of the methodical design system

5 Reference model

A top-down modeling approach is applied to design the reference model on all relevant system levels. The modeling proceeds through the design domains of AD, since they built the framework of the design method (Figure 4.4). Each modeling aspect links models and diagrams to the components of the design system (Figure 5.1). Three partial models, a function-object model, an object model, and a process-object model result as overall reference model to normatively explain the matrix production system for personalized production. The process-object model contains a model of the product architecture of to be produced products.

To construct the reference model, the AD design parameters are assigned as follows:

- CA represent the production operations.
- FR characterize the functional process needs of the operations.
- DP represent the processes of the production system.
- PV represent the physical elements of a production system. On the topmost level of the process decomposition, PV_i represents a functionally pre-instanced process module.

To enable the production system design, the model furthermore gives the following parameters:

- Process modules (PM) transfer functionally pre-instanced process modules (PV) into the production system design. PM are instances of PVs.
- Cs represent the overall design constraints, against which the design is ultimately evaluated.

This chapter introduces (Section 5.1) and verifies (Section 5.2) the reference model.

5.1 Setup of the reference model

For the introduction of the reference model, each of the three partial models are described, starting with the setup of the function-object model (Section 5.1.1) and the specification of functions and constraints (Section 5.1.2). Reflecting the domain structure of AD (Figure 5.1), the setup of the object model (Section 5.1.3), and of the process-object model (Section 5.1.4) follow.

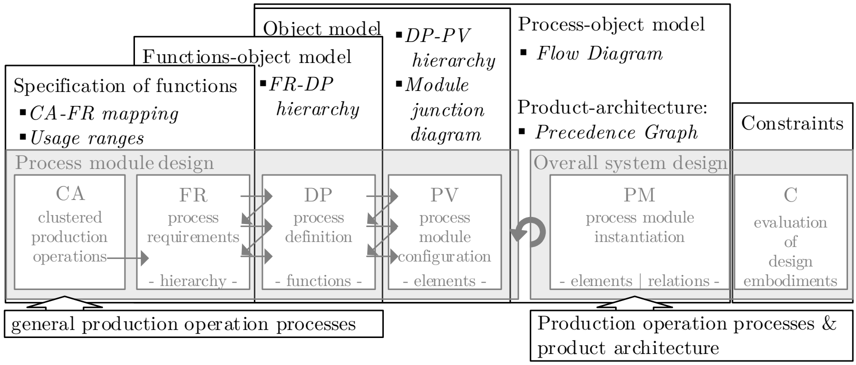


Figure 5.1: Setup of the reference model

5.1.1 Function-object model

The function-object model is a reference for the *FR-DP* mapping of the system design (Figure 5.1). It serves as a blueprint for the comparison of functional requirements and a system's process abilities. The model is defined through the decomposition of a general system segmentation into the subsequent levels of the personalized production system. Reference input constraints are identified for the topmost level of the decomposition.

5.1.1.1 General system segmentation

The highest functional requirement of a personalized production system design is to *produce high volumes of individualized products in a highly productive manner* (Figure 5.2). The production system is segmented into a customer-independent manufacturing segment (DP_1) and personalized production (DP_2). Intralogistics connects the two subsystems (DP_3).

Customer-independent manufacturing (DP_1) refers only to those manufacturing processes that are technologically incapable of producing a lot size of one efficiently. The focus of personalized production (DP_2) is the individualization of products, as demanded by the customers (FR_2). The *FR-DP* design hierarchy further decomposes personalized production into a subsystem of lot-size-one-capable value-add processes (DP_{21}) and into a subsystem of lot-size-one capable material flow processes (DP_{22}). DP_{21}, thus, unites manufacturing and assembly technologies in one segment. DP_{22} realizes the material flow of parts and assemblies within this segment.

The overall system segmentation is a decoupled design (Equation 5.1): Manufacturing of customer-independent parts is always executed before a personalized manufacturing and

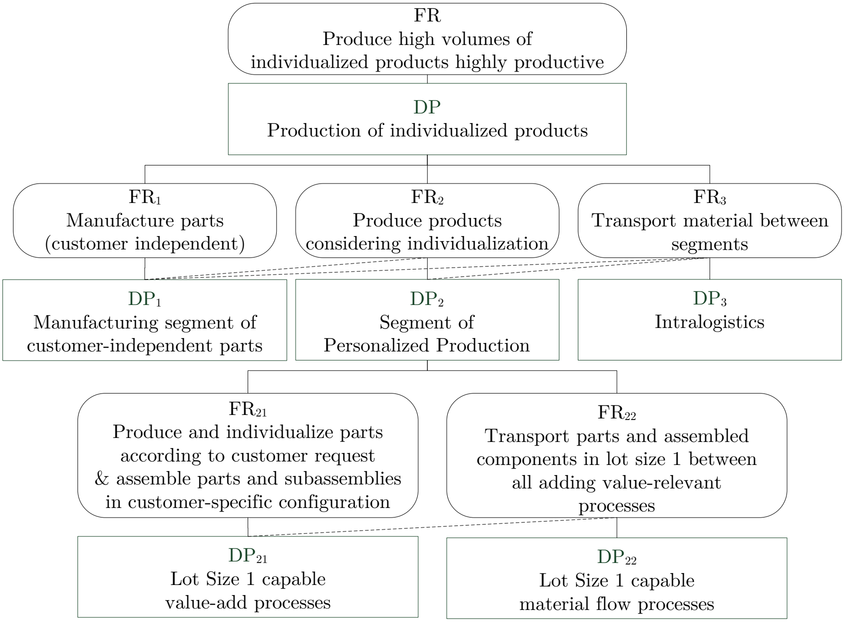


Figure 5.2: General system segmentation of a personalized production system

assembly, which makes the segment of personalized production (DP_2) generally dependent on the manufacturing segment (DP_1). Material transport is a support process, performed only when needed to enable the value-add processes. As such, DP_3 and DP_{22} are designed as dependent processes.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 \\ x & x & 0 \\ x & x & x \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad \begin{Bmatrix} FR_{21} \\ FR_{22} \end{Bmatrix} = \begin{bmatrix} x & 0 \\ x & x \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \end{Bmatrix} \tag{5.1}$$

The evaluation of alternative design embodiments is based on the input constraints for the system design (Figure 5.1). Input constraints must match the system characteristics of a competitive production system (Section 1.1). Reference constraints are accordingly determined to be:

C_1: Maximize changeability **C_2: Maximize productivity**

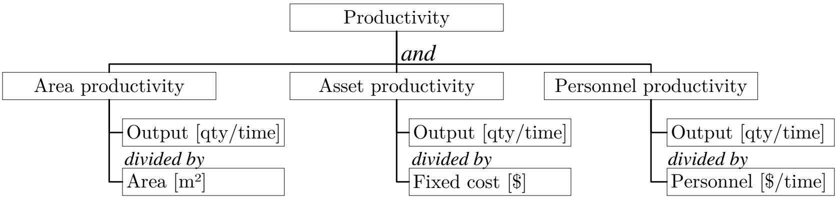


Figure 5.3: KPI system of productivity evaluation

Changeability has already been defined as a union of flexibility and reconfigurability (Section 3.1.1.3). There are changeability constraints that directly depend on the process requirements of actual and potential future production operations.

Production productivity is commonly indicated by the partial productivity KPIs of *personnel productivity*, *fixed assets productivity*, and *area productivity* (Table B.3, Appendix B). They are linked to each other in a KPI system (Figure 5.3), with the input parameters of needed personnel, fixed cost, and consumed area, and the output parameter of production volume.

On top of C_1 and C_2, other strategic input constraints, as well as overall non-functional requirements apply. Such constraints and requirements must be determined project-specifically. They are not linked to specific process requirements. Two important non-functional requirements are the overall output and the variant mix of a design project's relevant production program.

The evaluation of the system's overall changeability, productivity, and other input constraints is only possible on the system level, as they are influenced by the interaction of the system elements.

5.1.1.2 Personalized production system decomposition

Value-add (DP_{21}) and material flow (DP_{22}) processes are further decomposed into clusters of similar process requirements (FR_{211}...FR_{22x})[110] and mapped with appropriate manufacturing, assembly, and intra-logistical material flow processes (Figure 5.4).

manufacturing and assembly processes

FR_{211} ... FR_{21m}	produce or individualize parts of similar process requirements	DP_{211} ...DP_{21m}	suitable manufacturing processes
FR_{21n} ...$FR_{21(n+a)}$	assemble parts or subassemblies of similar process requirements	DP_{21n} ...$DP_{21(n+a)}$	suitable assembly processes

[110]At this state of the modeling, FR_{211} to FR_{22x} are only introduced generically. The following section on the specification of functions (Section 5.1.2) specifies them.

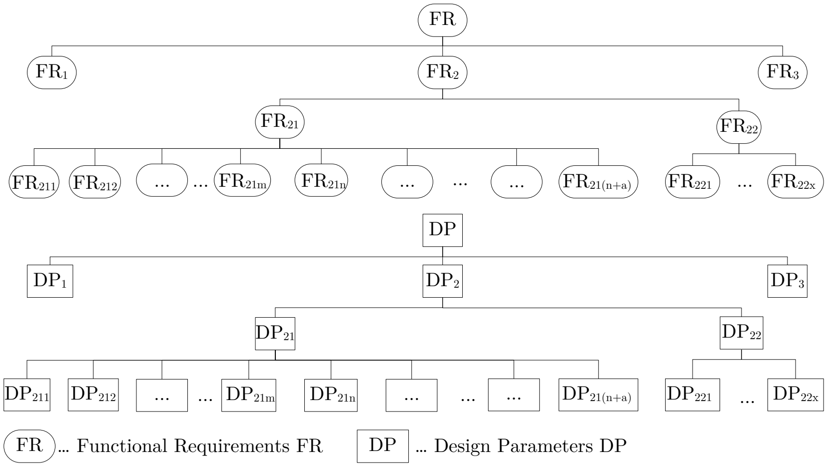


Figure 5.4: Decomposition of the personalized production system segment

material flow processes

FR_{221} ...FR_{22x}	transport parts and subassemblies between value add processes considering material flow requirements	DP_{221} ...DP_{22x}	suitable material flow processes

Material flow requirements (FR_{221}...FR_{22x}) depend on the state of the product, determined by a prior value-add process. The model separates manufacturing and assembly within the value-add processes. Manufacturing is a single-stage material transformation process. Assembly requires the two stages of building and joining a geometry[111]. Both assembly and manufacturing processes eventually contain preparation and post-processing actions[112]. Material flow is considered to be a process without preparation or postprocessing (Figure 5.5). The underlying assumption is that of a value-add core process, or its postprocessing support process, preparing each processed part or sub-assembly sufficiently for a subsequent factory load case of transportation.

The *FR-DP* mapping promotes an ideal design with a clear one-to-one mapping of processes (DP_i) to process requirements (FR_i) (Equation 5.2). This design decision for independence creates functionally separated, independent value-add process modules in the subsequent mappings. Likewise, material flow functions and value-add functions are to

[111]The model does not treat *build geometry* and *join geometry* as independent processes, as a built geometry is usually not stable without the subsequent fixation of parts. Depending on the applied assembly technology both activities may be performed in one assembly operation.

[112]The actually applied core process technology and the state of processed materials determine the necessity of support processes. Support processes may be manufacturing or assembly processes. Typical support processes are e.g. heating and cleaning.

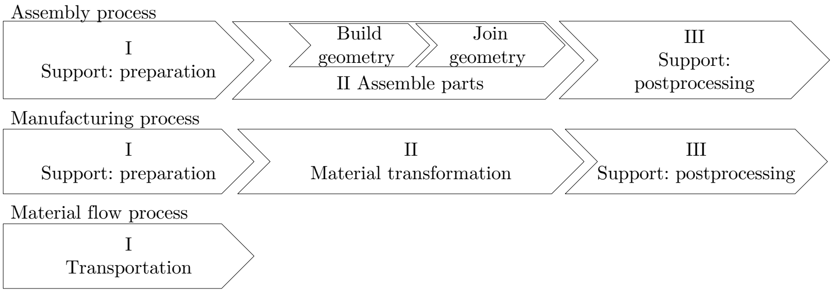


Figure 5.5: Subprocesses of assembly, manufacturing and material flow

be kept independent of each other, to prevent time-dependent complexity (Section 2.1.3). The defined system constraint of independent value-add and transport processes needs to be incorporated into the subsequent decomposition and design of the production system.

$$\begin{Bmatrix} FR_{211} \\ \dots \\ FR_{21m} \\ FR_{21n} \\ \dots \\ \dots \\ FR_{21(n+a)} \\ FR_{221} \\ \dots \\ FR_{22x} \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP_{211} \\ \dots \\ DP_{21m} \\ DP_{21n} \\ \dots \\ \dots \\ DP_{21(n+a)} \\ DP_{221} \\ \dots \\ DP_{22x} \end{Bmatrix} \tag{5.2}$$

5.1.1.3 Process decomposition

The process requirements are further decomposed down to the level of their activities[113] (Figures 5.6, 5.7 and 5.8). Functional activities are shared among the different processes (Table 5.1). While a material flow process needs considerably different activities, manufacturing and assembly processes differ primarily in the number of processed parts.

The topmost activity level of the decomposition is a decoupled design. The design of the value-add subprocesses DP_{21m3}, DP_{21n4} and DP_{22x2}, determine all other subprocesses,

[113]Any process is composed of a sequence of activities (Section 2.1.1).

Function		Activity PV_i (classes)	Examples/Descriptions PV_i instances	Model references
F1	Guide handling device	Handling manipulators	Workers, robots or similar to perform handling operation	FR_{21m11}; FR_{21m21}; FR_{21m41}; FR_{21m51}; FR_{21n11}; FR_{21n21}; FR_{21n31}; FR_{21n51}; FR_{21n61}; FR_{22x11}; FR_{22x31};
F2	Define pick position	Centering fixtures	Orientation of blank material to enable picking	FR_{21m12}; FR_{21m22}; FR_{21n12}; FR_{21n22}; FR_{21n32}; FR_{22x12}
F3	Connect to material transport system	Part Buffer	Interface to intralogistics, hand-over or drop-off installation	FR_{21m13}; FR_{21m23}; FR_{21m42}; FR_{21m52}; FR_{21n13}; FR_{21n23}; FR_{21n33}; FR_{21n52}; FR_{21n62}
F4	Contact, transfer & place	Material transfer system	Device or tools gripping parts during handling, usually guided by the handling manipulator	FR_{21m14}; FR_{21m24}; FR_{21m43}; FR_{21m53}; FR_{21n14}; FR_{21n24}; FR_{21n34}; FR_{21n53}; FR_{21n63}; FR_{22x13}; FR_{21x32}
F5	Guide value add process	Process manipulator	Machine, robot or worker executing a manufacturing or assembly process	FR_{21m31}; FR_{21n41}
F6	Transfer manufacturing forces	Manufacturing machine or device	Machine or device to transfer machining force to tool, usually guided by the manipulator	FR_{21m34}
F7	(Re-)shape, machine or change material properties	Manufacturing tool	Devices or tools actually performing manufacturing	FR_{21m35}
F8	Transfer joining forces	Assembly machine or device	Machine or device to transfer assembly force to tool, usually guided by the manipulator	FR_{21n45}
F9	Join parts	Assembly tool	Device or tool actually performing assembly	FR_{21n46}
F10	Define part position	Jig	Device or method to guarantee part position during manufacturing or assembly process	FR_{21m32}; FR_{21n42}; FR_{21n43}
F11	Define auxiliary position	Auxiliary holder	Device or method to guarantee correct position of process auxiliaries (liquid or firm) during manufacturing or assembly process	FR_{21m33}; FR_{21n44}
F12	Move goods	Transport manipulator	Vehicle, robot, or worker performing intralogistics transport process	FR_{22x21}
F13	Hold save during transport	Transport fixture	Device or methods to guarantee a safe position of parts during transport; usually connected to the transport manipulator	FR_{22x22}

Table 5.1: Process module functions

e.g., if auxiliaries are needed or residues are produced (Equations 5.3, 5.4 and 5.5). This coupling affects all sublevel decomposition of the design as a system constraint.

$$\begin{Bmatrix} FR_{21m3} \\ FR_{21m1} \\ \vdots \\ FR_{21m5} \end{Bmatrix} = \begin{bmatrix} x & 0 & \cdots & 0 \\ x & \ddots & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ x & 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP_{21m3} \\ DP_{21m1} \\ \vdots \\ DP_{21m5} \end{Bmatrix} \tag{5.3}$$

$$\begin{Bmatrix} FR_{21n4} \\ FR_{21n1} \\ \vdots \\ FR_{21n6} \end{Bmatrix} = \begin{bmatrix} x & 0 & \cdots & 0 \\ x & \ddots & 0 & \vdots \\ \vdots & 0 & \ddots & \vdots \\ x & 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP_{21n4} \\ DP_{21n1} \\ \vdots \\ FR_{21n6} \end{Bmatrix} \tag{5.4}$$

$$\begin{Bmatrix} FR_{22x2} \\ FR_{22x1} \\ FR_{22x3} \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 \\ x & x & 0 \\ x & 0 & x \end{bmatrix} \begin{Bmatrix} DP_{22x2} \\ DP_{22x1} \\ DP_{22x3} \end{Bmatrix} \tag{5.5}$$

On the next level of decomposition, the idealized model states that the activities are independent of each other (Equation 5.6) to prevent time-dependent complexity (Section 2.1.3) between the activities during operation.

$$\{FR_{m,n,a}\} = \begin{bmatrix} A \end{bmatrix} \{DP_{m,n,a}\};$$
$$\text{where } \begin{bmatrix} A \end{bmatrix} = diag(x, ..., x); m = (21m11...21m41; ...; 21m51...21m53) \tag{5.6}$$
$$n = (21n11...21n14; ...; 21n61...21n63); a = (22x11...22x13; ...; 22x31...22x32)$$

5.1.2 Specification of functions

So far, manufacturing, assembly and transport requirements FR_{211} to FR_{22x} have only been introduced generically (Section 5.1.1.2). In a production system design, they have to be made specific. The specification of functions is a reference for the CA-FR mapping of a system design (Figure 5.1). The functional requirements transform the requirements into the design process. The specification of functions is achieved through a clustering of production operations into CA_i and through the quantification of the according FR_is' usage ranges.

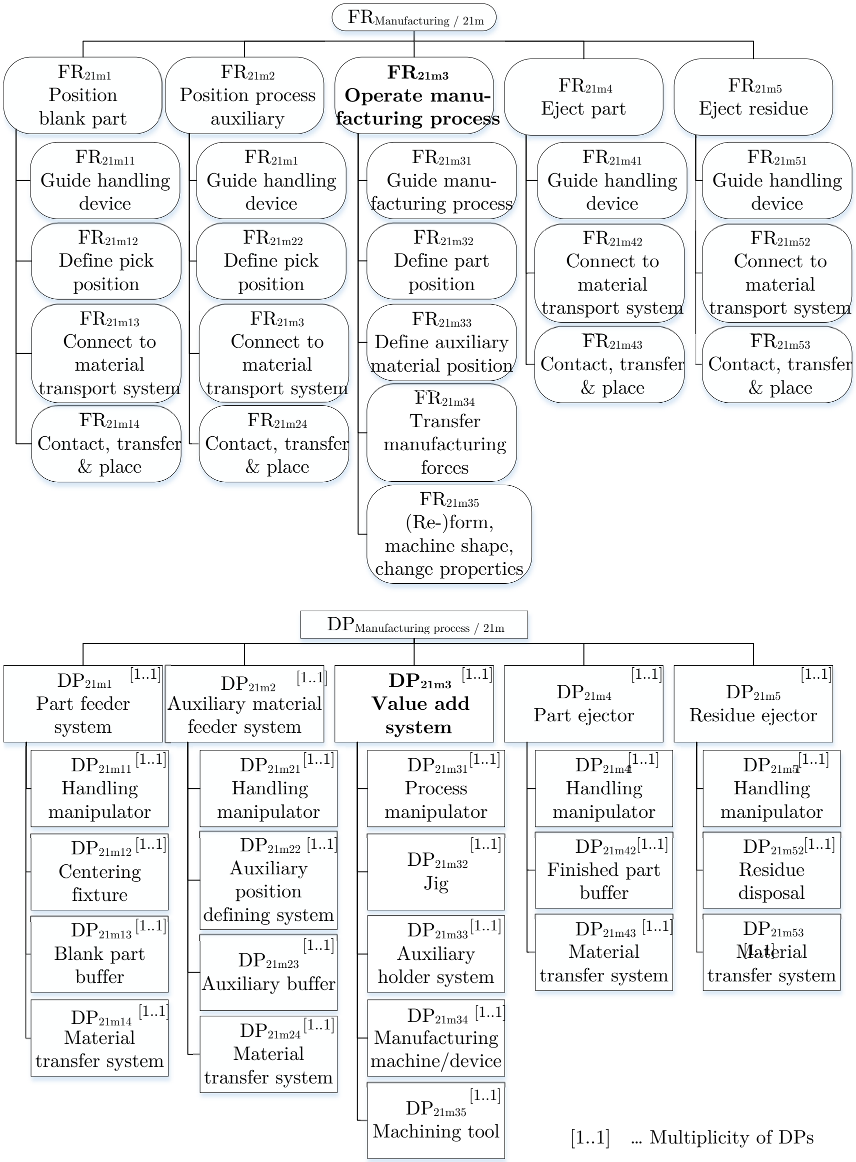


Figure 5.6: Function-object model of manufacturing processes

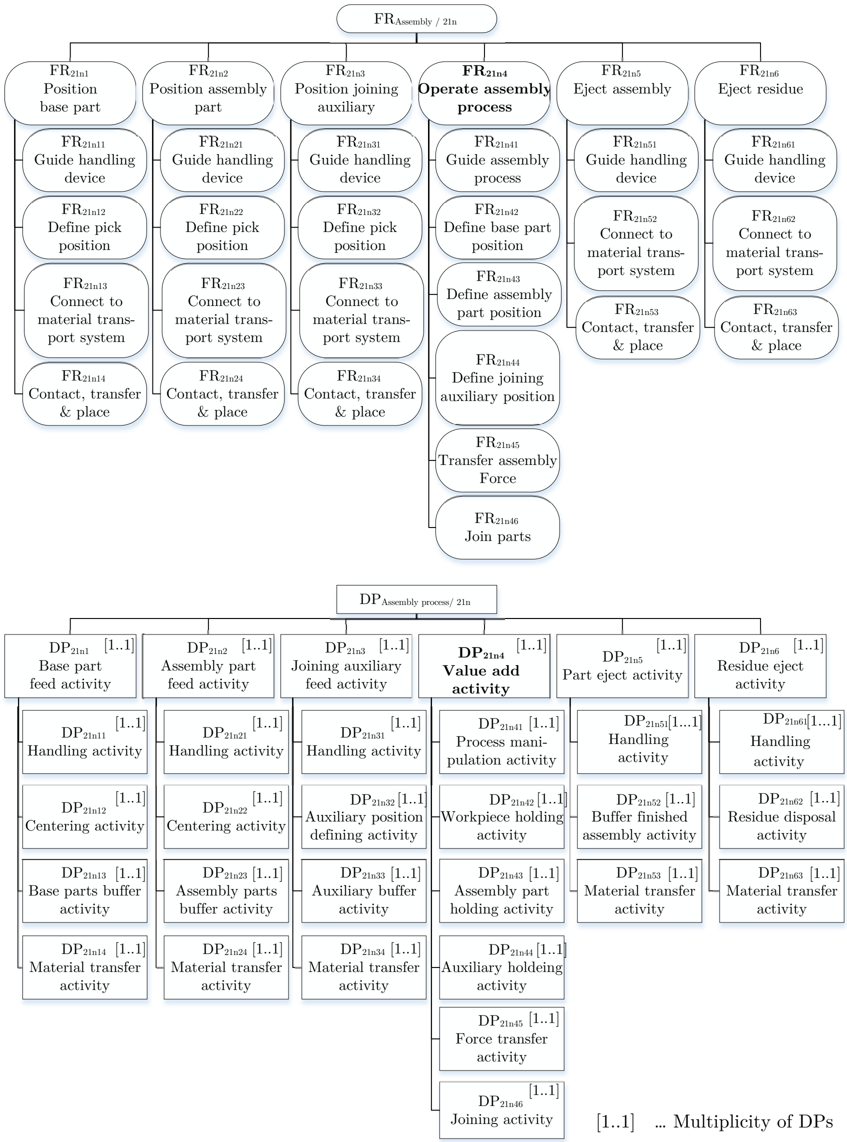


Figure 5.7: Function-object model of assembly processes

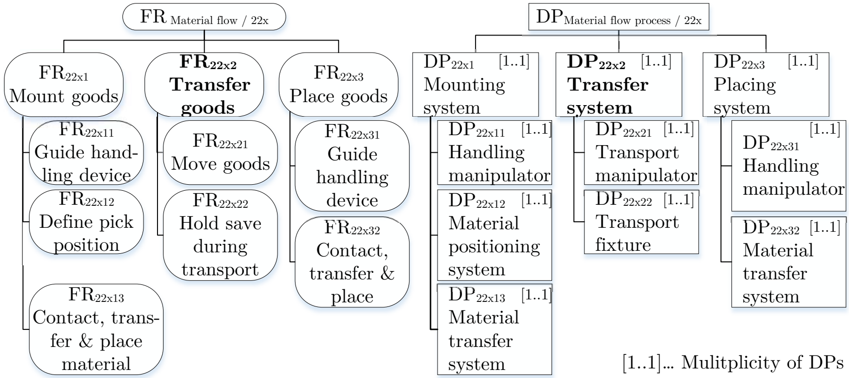


Figure 5.8: Function-object model of material flow processes

5.1.2.1 CA-FR mapping

The *CA-FR* mapping must result in CEME FR_i (Section 4.2.3). CA_i cluster similar production operations[114] (Figure 5.9). The clustered operations are functionally coupled. This does not mean that they need to be executed in a production system instantiation at the same time. But they are executed by the same system functions.

Each CA_i is assigned with a FR_i. In the subsequent *FR-DP-PV* mapping, each FR_i is ultimatively assigned with a physical production system element for production operation execution. Therefore, it must be conceivable that all manufacturing, assembly, or material flow operations clustered in one CA_i may be successfully fulfilled through a sequence of similar processes, executed through identical instances of production system elements. In the logic of AD, this integration of different, functionally-similar production operations into one CA_i prevents a functional coupling of different production system elements, which would arise if there was a specific *FR* defined for each production operation.

AD aims to minimize the number of FR_i (Corollary 2) and to specify broad allowable functional ranges (Corollary 6) (Appendix C.3). An integration of a large number of multiple operations into CEME CA_i must thus be pursued by design. The integration of a large number of different production operations into one CA_i ultimately increases the functional universality of production system elements and reduces the total number of functionally different production system elements.

[114] In line with the definition of production (Section 2.1.1), examples of operations are a certain machining of a part, the assembly of two parts, or the transportation of a part or an assembled component to a and between PM.

		CA_1	CA_2	...	CA_n
Product A	operation A1	x			
	operation A2		x		
	operation A3	x			
	...			x	
...	...	x			
Product N	operation N1	...			...
	...	x			
	operation Nn				x

CA-FR mapping (exemplary):

$CA_1 \rightarrow FR_{21m}$

$CA_2 \rightarrow FR_{21n}$

...

$CA_n \rightarrow FR_{22x}$

Figure 5.9: Assignment of operations to customer attributes

5.1.2.2 Functional usage ranges

Each CA-FR mapping is associated with desired usage ranges for FR specification. The usage ranges reflect given tolerances and changeability requirements of the production operations that are clustered in a respective CA_i. To quantify tolerance requirements and corresponding functional process capabilities of a personalized production system, design range dr and system range sr, as defined by Suh (Section 4.2.3), are applied. They are introduced as requirements and attributes of a process module or process module element and indexed with *is* and *future*:

- The permissible tolerance range of an actually known production program's processes is represented by the design range dr_{is}.
- A potentially narrower future tolerance requirement is reflected with dr_{future}.
- The system ranges sr_{is} and sr_{future} describe the process abilities of a system element.

To quantify changeability requirements and capabilities, further design and system ranges are introduced. In line with the definition of changeability as a union of flexibility and reconfigurability (Section 3.1.1.3), they are stated as follows:

- The required flexibility corridor of known and planned product variants is given through a flexible design range fdr, or a (set of) flexible design points (fdp, FDP).
- The flexibility provided by a production system element instance is accordingly called flexible system range fsr or (set of) flexible system points (fsp, FSP).
- In analogy, the requirements of potential future variants are covered by a reconfigurable design range rdr or a (set of) reconfigurable design points (rdp, RDP)[115].
- Reconfigurability, provided by a production system element instance is introduced as reconfigurable system range rsr or (set of) reconfigurable system points (rsp, RSP).

Tolerance and changeability ranges are expressed in the dimensions of change barriers. A change barrier is defined as a category by which the limits of use of a technical system can

[115] Although changeability is understood by some as a system characteristic without predefined limits (Section 3.1.1), the introduction of the reconfigurable design range rdr and RDP seems reasonable, as otherwise any system would have to be designed for infinite future requirements.

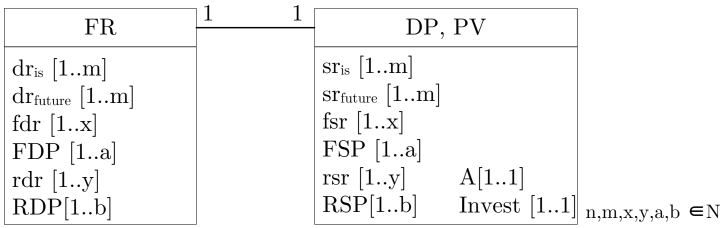


Figure 5.10: Multiplicity of change barriers

be quantified. A change barrier may be any technological, technical, or socio-organizational limitation of a process. A quantified change barrier is an inherent characteristic of the production system. It is related to specific product and process properties given by the product design or tied to a system property given by the system design. A change barrier prevents the change from one process variant to another or the integration of additional processes into a process module if the given limits of the change barrier are exceeded. Hence, the existence of a change barrier makes universality of process modules impossible.

FR-DP-PV mappings are associated to several change barriers (Figure 5.10). Within each change barrier, actual and future permissible tolerances as well as actual flexibility and future reconfigurability requirements are given. A quantification of system ranges is usually only possible, once a physical system element for process execution is assigned in the mappings.

Through the hierarchical interrelation of process module subsystems with their production system, production system elements influence a system's overall performance directly. Therefore, DP_i and PV_i are further quantified by their individual share of area consumption (A) and investement cost (Invest) on the input constraints[116] (Figure 5.10).

5.1.3 Object model

The object model is a reference for the *DP-PV* mapping of the system design (Figure 5.1). Production system elements are assigned to all DP_i for activity execution which synthesize the processes and thus satisfy the FR_i. In order to stay generic, the reference model only includes element classes (Table 5.1). When these elements are instanced by a design, a functionally pre-instanced process module is created.

The module representation of the *DP-PV* mapping constructs the object model, with PMs as elements of the personalized production system (Figure 5.11). Modules M_1 and M_3 represent the manufacturing segment of customer-independent parts and the intralogistics

[116] The input factor of personnel requirement for the calculation of personnel productivity is missing from this list, as this factor depends from the process time of an actual production program's operations.

system of the general system segmentation (compare Figure 5.2). M_2 represents the matrix production system. Lot-size-one-capable manufacturing and assembly process modules (PM_{211} to $PM_{21(n+a)}$) are combined into the module M_{21}. Module M_{22} contains the material flow process modules (PM_{221} to PM_{22x}).

The reference object model states an ideal as well as a decoupled redundant design as acceptable (Figure 5.11). Each process DP_i is assigned with one to n process module (PM) instances in the mapping. In the case of multiple instances, every instance delivers the same functional processes abilities with the same elements (PV_i). This allows for a harmonization of differing capacity requirements of different production operations. An instanced matrix production system thus contains several process modules (PM) of the same DP_i, and the same PV_i, allowing for a dynamic distribution of work between different instances of same-functional PMs during system operation (Section 2.1.4.2).

The production system element mapping on the activity level of the decomposition models the internal architecture of the process modules (Figure 5.12). Process modules are modular in design. As on the process level, the modules reflect the *DP-PV* mapping of the function-object model (Figure 5.6, Figure 5.7, and Figure 5.8). The dependency of all other activities from a process module's value-add system, as defined by the function-object model (Equations 5.3, 5.4 and 5.5), is transfered into the object model.

5.1.4 Process-object model

So far, only the functional mapping between process requirements, processes and production system elements are represented by the function-object model and the object model. When being built, a product usually needs a sequence of manufacturing and assembly processes. In an instanced production system, the respective coupling of value-add PMs is realized by material flow PMs. The system control command (SCC) of the process-object model flow chart (Figure 5.13) determines all possible material flow relations between a system's PMs. In the idealized process-object model, the system operation allows for a coupling of independent value-add PM by any material flow PM. The coupling is of dynamic nature. A flexible route is only built on demand, depending on the production operation sequence and the specific process requirements of the product in production. Without an actual requirement for a coupling of process modules through the production process, all functionally-independent PMs are uncoupled.

The product is modeled by a precedence graph which carries the process requirements of each required production operation as well as the requirements of the material flow operations (Figure 5.14). The precedence graph discloses the architecture of produced products. It shows the degrees of freedom of the operation sequence with the two possibilities of a parallel (upper part of Figure 5.14) and sequenced (lower part of Figure 5.14)

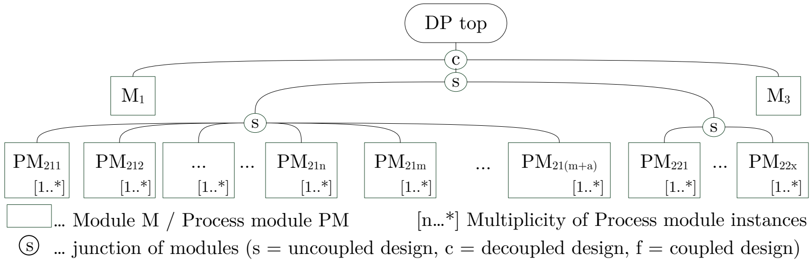


Figure 5.11: Module junction diagram of a matrix production system

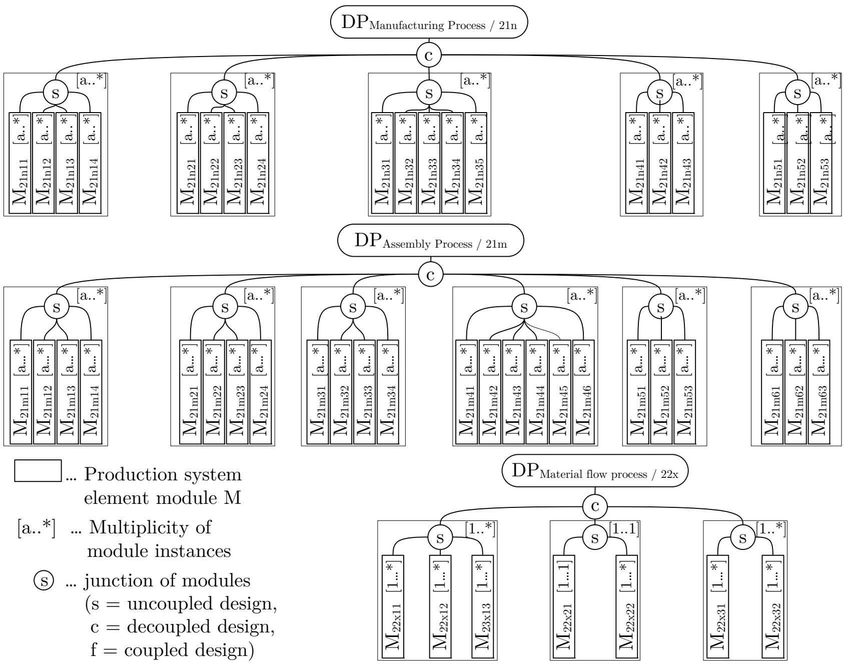


Figure 5.12: Module junction diagram of process modules

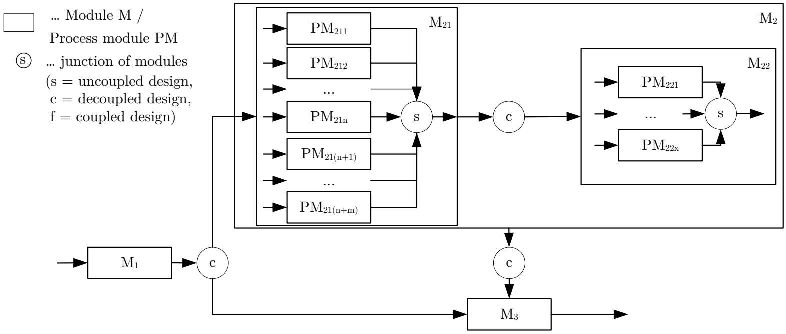


Figure 5.13: Flow chart of a matrix production system

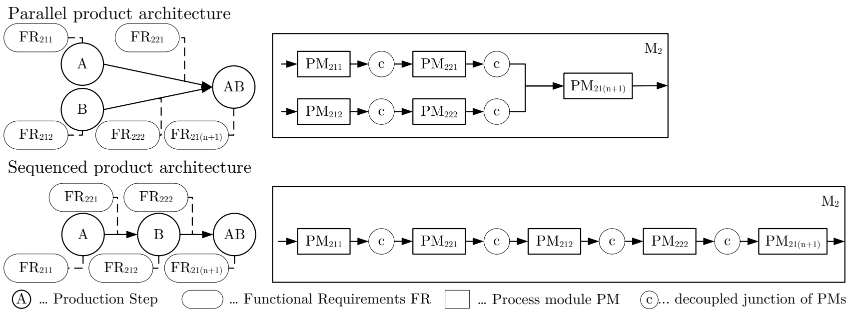


Figure 5.14: Dependency of product architecture and dynamic system architecture

execution of processes. The process-object model builds the foundation for the design of the process module (PM) relation in a system layout (Figure 5.1).

5.2 Discussion and verification of the model

The model is a conceptual design of a matrix production system, as it anticipates a system that is not yet existent in reality (Section 1.4.1.2). It is built as a qualitative model, using the notation of AD for Systems. The model presents the fundamental organizational structure and operative behavior of a matrix production system. It is to be used as a normative reference model, supporting the problem-solving process during production system design. With respect to this purpose, it is not necessary for the model to represent the system in all details. Only sufficient, design-relevant aspects need to be included. A production system designer must be able to instantiate the model when creating an engineering draft of the production system with a realization plan that is to be delivered through the design method.

In line with J. Müller's (1990) assumption of truth (Section 1.4.1.2), it is not necessary to check the consistency of the model against an existing reality, but there must be a high plausibility to build a future reality. The guiding question for the verification is, thus, how well the model achieves a set of goals, and not so much how well a reality is mapped. The model is verified in the following sections by logical reasoning, relative to the model requirements (Table 4.2), following J. Müller's criteria for the examination of the feasibility of a conceptual design (Section 1.4.1.2) and Patzak's criteria of a good model (Section 4.1.1).

According to J. Müller's criteria for a feasible conceptual design, it must be possible to *implement* the model, the modeled system must *fulfill its functional requirements*, and the model must be *acceptable* for the system designers (Section 1.4.1.2). Only a correct model can be implemented. According to Patzak, correctness must be tested in the two dimensions of *empirical correctness* and *formal consistency*, and a model is acceptable if it is *useful*, *practicable* and *parsimonious* (Section 4.1.1). For a production system model, empirical correctness is based on *structural* and *functional correctness* on all *hierarchical* system levels (Figure 2.4). Functional validity thereby incorporates J. Müller's criterion to fulfill functional requirements. The user acceptance of the reference model can only be tested, when it is applied during a detailed production system design. The reference model's use and acceptability by the system designers will thus be verified with the application of the methodical design system in the validation case (Section 7.3).

Therefore, the reference model is considered verified if its structural and functional correctness and its formal consistency are given (Sections 5.2.1, 5.2.2, 5.2.3).

5.2.1 Structural verification

For structural correctness, the reference model needs to map all design-relevant production system elements and relations adequately. The object and the process-object model display the dependency between product architecture, product functions, and the production system (Requirement **R2.2**, Table 4.2). The process flow diagram and model map the flexible routing and the interdependence to the product model (Requirement **R2.3**, Table 4.2). The product model only models the aspects that are relevant to this flexible routing, i.e., the product architecture and the functional requirements. To test for structural validity, the extrema of the structural setup of the system (Figure 5.11) are discussed on the production system level (Table 5.2).

Table 5.2: Cardinality of structural elements at the production-system level

Structural element	**Number of structural elements**	
Value-add process modules (PV_i)	~~1~~	n≥2
Material flow process modules (PV_i)	1	n
PM instances of each value-add process module	1	n
PM instances of each material flow process module	1	n
PM instances of process module relations	1	n

($n \in \mathbb{N} > 1$)

- The model is valid for the extreme of $FR_{max} = n$, with n being the number of independent production operations: The model does not limit the maximum number of process modules in the production system and the number of relations. For an ideal design, each FR_i is mapped in a one-to-one mapping with a DP_i and a PV_i.
  In the case of $FR_{max} = n$, there is one dedicated functionally pre-instanced process module (PV_i) for any process operation, tailored to execute only this specific operation. Consequently, there is at least one PM instance for each production operation. Such a system would result in a tremendous amount of transports to realize the material flow between the high resulting number of process module instances with a potentially negative impact on productivity. From a functional perspective, however, this is a possible setup of the system.
- The lower limit is given by the object model which defines at least one material flow process. According to the process-object model, this means at least two value-add processes, to be connected by this single material flow process. It follows that $FR_{min} = 3$.
  In the case of $FR_{min} < 3$, the overall system would be built by value-add process module instances of exclusively one functionally pre-instanced process module (PV_i). Each of these PM would need the capability to execute all required value-add operations, to build all product variants completely. There would be no transport between value-add PMs required. It is unthinkable to integrate all needed processes for the high variety of individualized products into one process module, especially if a certain degree of automation is pursued. It is also not a desirable system for personalized production, as it lacks a flow within the production system. Accordingly, the model does not allow for a system of only one value-add FR. The model does, however, allow a very limited number of different FR_i.
- According to the object model, any PV_i must be instanced at least one time and may be instanced multiple times. If no instance is realized, the production system will lack the function of the required processes. Multiple instances are justified by the capacity requirements of an actual production program.

Table 5.3: Cardinality of structural elements within a process module

Structural element	Number of structural elements		
Classes of value add process module elements	—	1	~~n~~
Classes of material flow process module elements	—	1	~~n~~
Instances of value add process module elements	0..1	1	n
Instances of material flow mounting and placing system and -elements	0..1	1	n
Instances of material flow transport system and -elements	0..1	1	~~n~~

($n \in \mathbb{R} > 1$)

The object model of the internal architecture of the process module maps a production system element to each FR_i (Figure 5.12). The following structural extremas are covered (Table 5.3).

- Classes of value-add and material flow elements are only contained once within one process module, to incentivize a good process design. If the number of classes exceeds one, the design would be redundant or coupled[117].
- The model allows for multiple instances of each value add element within one process module. The multiplicity of instances is realistic to meet capacity requirements. Multiple instances also allow for a parallelization of processes[118].
- Instances of process module elements may even be smaller than one, if they are shared by different process module instances[119].
- Instances of material flow mounting and placing system and -element are also valued with an instance of less than one, if several parts are transported at the same time. They need to be instanced multiple times per material flow PM, if mounting and placing of goods must be performed by several elements to cover capacity requirements.
- The model restricts the maximum number of instances of transport systems and elements to the number of one. This is reasonable, since any number of transport

[117] It may be necessary to violate this ideal model, if a bad product design forces the production system designer to design a non-ideal process. A bad product design could, e.g., cause the need to assemble more than one part at once. It is the task of the system designer, to then try to alter product or process design to be able to minimize the number of FR_i and achieve a good, ideal, or decoupled overall design.

[118] A parallelization of processes may be useful for the assembly of several identical parts within a product.

[119] A sharing of instances occurs, if one process module element instance is not fully utilized (e.g. a shared material buffer), or if it is used by another process module instance during a waiting time (e.g. use of a value add system by two different process modules to keep it utilized during produced goods discharge).

system and -elements larger than one would inevitably result in another material flow PM.

To summarize, the structural correctness of the module can be assumed.

5.2.2 Functional verification

Functional correctness is associated with the functions of the production system. The model must sufficiently describe the functional system abilities for the system deisgn on different system hierarchy levels (Requirement **R2.1**, Table 4.2). On the system level of production, the reference model meets this requirement with the following characteristics:

- The model separates manufacturing, assembly and material flow processes. Functions and system abilities are kept generic in the model. The model is, thus, universally valid for different assembly and manufacturing technologies and may furthermore be applied to map both the material flow of supplied materials, as well as the flow of produced goods.
- The model assigns a process and process module elements to each FR_i. It is thus ensured that each production operation is assigned with an appropriate process module.
- The model is open in regard to the number of process requirements and emerging process modules. For an ideal design, each FR_i is mapped in a one-to-one mapping with a DP_i. It is thus possible to fit the total number of processes to the given diversity of product functions, expressed by the number of different FR_i.

On the subjacent levels of decomposition, the following characteristics of the reference model support its functional correctness:

- The function-object model does not only contain value-add elements but also the necessary material handling elements to enable a process (Section 2.1.1).
- Mounting and placing goods from and to transport is integrated into the model of the material flow process. The model thus incentivizes the system designer to strive for a separation of value-add and material flow processes to the greatest possible extent.
- The process decomposition ends at the point where it is possible to remain conceptual. When a system needs to be developed, any last-level leaf of the decomposition tree could be further decomposed, e.g., if there is no sufficient solution available on the market to satisfy the requirements of the specific use case.
- The function-object model is built as a decoupled model, to force system designers to design value-add processes first.
- A comparison of functional requirements and alternative system design solutions is possible, regarding the suitability of system abilities to fulfill actual and future

permissible tolerances, as well as actual flexibility and future reconfigurability requirements within the categories of the change barriers. The model only gives the categories of change barriers. It does not specifiy the actual change barriers and it does not limit the multiplicity of change barriers as system function values. It is thus possible to model multiple variants of a process, including different degrees of automation according to specified change barriers.

Even though the reference model is a normative model, the function-object model of the process modules has descriptive elements. It is thus possible to verify the model by comparison with state-of-the-art production machinery and equipment. In the production system design for the validation case of this thesis (Chapter 7), it was possible to map all existing assembly workstations and production machines of the industrial partner. Furthermore, the function-object model on the process module level has been applied for a gripper system design of a body-in-white robot cell (Foith-Förster et al. 2016). During the design, the completeness of the model was discussed and reviewed with production system designers of the Daimler AG. It was possible to map all required functions of the robot cell with the model.

All in all, a functionally correct reference model can be assumed. Together with the structural correctness, argued above, the reference model is considered to be empirically correct. The reference model, furthermore, proved its applicability for the validation case of this thesis (Chapter 7), for which all partial models were instanced and discussed with the production system designers and production managers of the industrial validation partner.

5.2.3 Formal consistency

Formal consistency of a model can be assumed if a model does not show any irregularities within its components and if it is modeled without mistakes in the modeling notation. The common modeling notation of AD for systems enables a consistency check by members of a professional community. A formally consistent reference model can be assumed for the following reasons:

- The peer-review of the above-quoted publication of the function-object model (Foith-Förster et al. 2016) did not find any inconsistencies or mistakes in the notation.
- Furthermore, the reference model was published as peer-reviewed conference paper (Foith-Förster et al. 2019). The paper won the *Park's best paper award* at the 2019 annual International Conference on Axiomatic Design.

With the discussed structural and functional correctness and formal consistency, a correct reference model is assumed.

6 Design method

A production system designer needs appropriate methods and tools to design a matrix production system for personalized production (Section 4.1). This chapter describes the design process (Figure 6.1), gives guidelines and the calculation rules to decide on alternative design solutions, and introduces methods and tools for a specific instantiation and evaluation of the production system design. It is organized along the decision theory of E. Heinen (Section 4.1.3): Section 6.1 focuses on the *consideration* and *decision on alternative design solutions* for a suitable process module design. Section 6.2 explains how to *implement* the process modules in an overall production system design and *review* the system design through an evaluation of design embodiments.

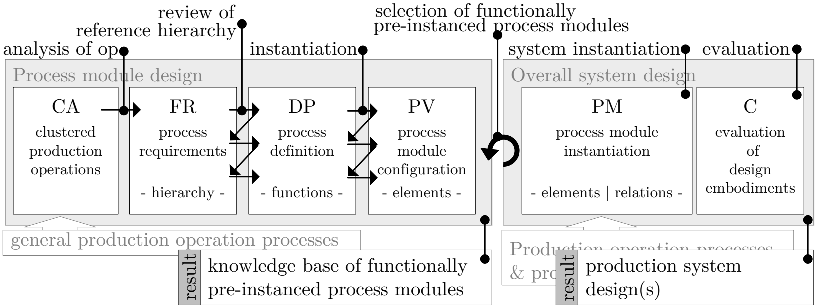


Figure 6.1: Setup of the design method

6.1 Process module design

Process modules are the elements of a matrix production system (Chapter 5). In a process-oriented design approach (Chapter 1.3) they need to be functionally defined prior to the overall system design. Generally, production system functions derive from the process requirements of to-be-produced products (Chapter 5.1.2). Process modules must match a company's product spectrum and production business case.

Only some of the general objectives for a personalized production system (Section 1.1) can be influenced by a system's functional design. Flexible and reconfigurable process modules deliver a system with the capability for product flexibility, the capability to integrate new product generations and technologies, and the possibility to accordingly invest into required production equipment step-by-step. Effectively, a process module design should be valid for re-occurring instantiations for different production programs. Process modules are, therefore, functionally pre-instanced and saved in a knowledge base of process modules, to be instantiated by a subsequent production system design (Figure 6.1). This section explains how to develop process module pre-instances by design goal clarification (CA-FR mapping), process module hierarchy affirmation (FR-DP mapping), and functional configuration of process modules (DP-PV mapping).

6.1.1 Process module design goal clarification (CA-FR)

Following the design process of AD (Section 4.2.3), the clarification of the design goals is the very first step to achieve a successful design. Design goals are derived from CA. The CA of the process module design relates directly to the respective manufacturing, assembly and material flow operations needed to produce certain products (Figure 5.9). There are four AD corollaries (out of eight) that are relevant to the process module design goal clarification[120]:

- **Corollary 1**: *Decoupling of coupled designs*
- **Corollary 2**: *Minimization of FRs*
- **Corollary 6**: *Largest design ranges*
- **Corollary 7**: *Uncouple design with less information*

Due to AD's mapping of design domains, a minimization of independent FR_i (Corollary 1, Corollary 2) requires a small absolute number of disjunct CA_i and results in a minimization of processes (DP_i) and process module elements (PV_i). To achieve a production system with a minimized number of functionally differing process modules and a minimized number of transports between process module instances during production process execution, a high universality regarding the capabilities of processes and respective process modules (Corollary 7) must be a design priority. A small number of transports between process modules (PM) has a positive impact on throughput time, as the amount of waiting time of an order in the input buffers of PMs is reduced. A high functional universality of process modules reduces the material flow complexity of the system, as more variants share a similar sequence of PM during production execution. Furthermore, the risk of an over- or underutilization of variant-specific process modules decreases, and the control complexity

[120]Appendix C.3 provides a complete list of all eight AD corollaries and explains them. Corollary 3 and Corollary 4, which are irrelevant to this step of process module design goal clarification, are applied in the subsequent steps of the design method. Corollary 5's request for symmetry is more relevant to the design of mechanical systems and will not applied for production system design. Corollary 8 details the quantitative measure of functional independence and is also not used explicitly in this thesis.

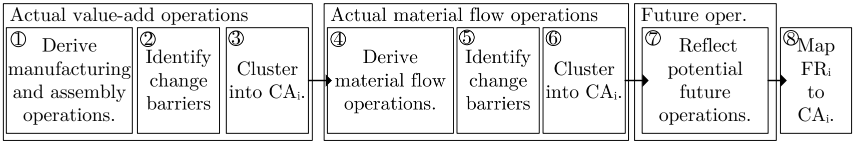


Figure 6.2: Eight steps to process module design goal clarification

is reduced to the task of order distribution between a higher number of functionally equal PMs, as more variants share the same process modules.

The total number of CA_i depends on the question of how broad the functional range of process requirements can be specified (Corollary 6), so that it is still possible to find a technical solution to execute efficiently all related operations of one CA_i on the same, accordingly mapped process module. Depending on the product's process diversity, there are one to n ($i = 1 \dots n$) CA_i in each of the categories of manufacturing, assembly and material flow. CA is derived in eight steps (Figure 6.2), described in the following.

Step 1: Derive all actual manufacturing and assembly operations.

All relevant, actual product variants are analyzed for lot-size-one-capable manufacturing operations and all needed assembly operations to built the product. This includes not only value-add core processes but also technologically-required preparation and post-processing operations. There is a significant level of detail necessary at this step, to prevent missing functional abilities in the instanced production system. As a rule of thumb, a change of manufacturing or assembly technology and any new part indicate a new production operation.

It should be prevented to split operations before a stable state of parts or assemblies is achieved. Any produced good must be ready for a factory load case of transportation or temporary storage after a completed process sequence. Processes that share their requirements and utilize the same technology on the same part, e.g. screwing four screws to assemble one lid (Figure 6.3), are to be treated as one operation.

The actual product spectrum is used as a representative to make this first step practicable. Due to the functional focus of this design stage, production operations are not yet associated to specific product variants or sorted according to a specific product architecture.

As input, existing SOO documentations, technical product drawings and manufacturing BOMs are to be used.

The result of this step is an unsorted list of manufacturing and assembly operations.

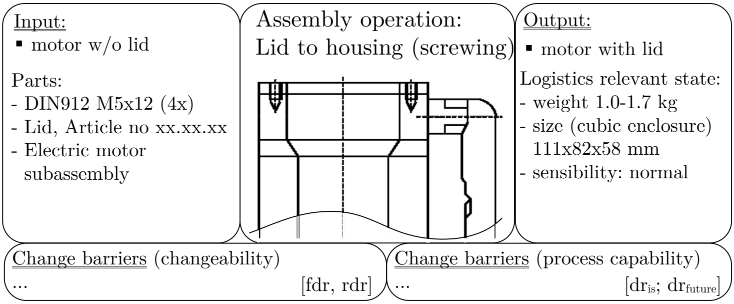


Figure 6.3: Change barrier and tolerance description of example assembly operation

Step 2: Identify change barriers of value-add operations.

The second step introduces the *change barrier analysis*. Change barriers have been defined in the reference model (Section 5.1.2.2) as categories to quantify the limits of use of a technical system. The change barrier analysis is intended to help cluster operations into different CA_i, by delivering the sorting criterion of process inconsistencies. Instead of having to describe production operations by all their process attributes to identify process similarities, the change barrier analysis allows to concentrate only on the fewer process attributes that prevent an integration of different operations onto one process module.

Identifying the relevant change barriers is crucial for the success of the design. The following design process exclusively uses the change barrier categories for a comparison of alternative design solutions regarding flexibility and reconfigurability, and for a process segmentation of the production system. Intensive discussions of system designers and process experts are needed for the change barrier analysis. There are two guiding questions:

1. *Is a solution conceivable that enables to execute all value-add operations on one process module*[121]*?*
2. *If not, what is the criteria that forces the split?*

The function-object reference model of value-add processes[122] (Figures 5.6 and 5.7) is applicable as a framework for the change barrier analysis. Change barriers are associated to the DP-leaves of the decomposition trees. When addressing the guiding questions, the discussion may follow the respective manufacturing or assembly process module DP tree from root to leave.

[121] At this stage of the design, only the functional perspective is relevant. Capacity requirements resulting in multiple process module instances are considered in the succeeding design steps of the production system design (Section 6.2.2). All value-add operations refer to all operations of all product variants of the considered product spectrum (Step 1).

[122] The reference model separates manufacturing and assembly processes (Section 5.1.1.3), due to the inconsistency of their functions. Hence, the change barrier analysis needs to consider manufacturing and assembly operations independent of each other.

If there are technical, technological or organizational solutions conceivable, that enable to execute all value-add operations on one single type of process module, there are no relevant change barriers existent for the prevalent operations. In this case, the answer to the first question is yes. All processes are so consistent, that a functional execution of all customer-specific manufacturing operations is conceivable on one manufacturing process modules, and a functional execution of all operations to assemble all product variants is conceivable on one assembly process module.

If operations need to be split for technical, technological or organizational reasons, the criteria that force the split are the relevant change barriers of the system design. In assembly, automation is often considered to be a change barrier. Accordingly designed-for-automation operations need to be split from operations that are only designed for a manual execution, in order to implement fully automated production cells. Permissible tolerances can be considered a change barrier, as it might be economically undesirable or technologically unfeasible to operate processes with lower tolerance requirements on high precision equipment.

The identification of change barriers also has to do with required investments for the technical realization of operation execution. If it is possible to combine technical equipment in a highly integrated station for the sake of under-utilized high investment equipment, an integration should not be considered.

Production operations may be clustered into one CA_i if there are means available to achieve a switch-over between technical equipment in between two subsequent orders, in the sense of a date-oriented operational flexibility (Section 3.1.1.1). They may not be clustered into one CA_i if a period-oriented change-over of equipment is needed. The duration of the change-over would jeopardize the system's ability for one-piece-flow. A segmentation by time periods, i.e. the change over of parts or the whole system from one cluster of operations to another, is not a preferred design for a personalized production system design either, as it limits variant mix flexibility.

As input, the list of identified operations (Step 1) is needed. Furthermore, expert knowledge about possible technological, technical and organizational implementations of processes and process limitations is needed. The current state of the art of process technology and production equipment must be known to the planners. Furthermore, the function-object reference model of the value add process modules of assembly and manufacturing is to be used as a framework to guide the discussion.

The result is a list of relevant change barriers for the design of value-add process modules.

Step 3: Cluster manufacturing and assembly process steps to according CA.

Step 3 starts with a quantification of all value-add operations in the dimensions of all identified change barriers[123] (Figure 6.3). Furthermore, permissible tolerance requirements are quantified.

The quantification of change barriers and permissible process tolerances provides the basis to cluster operations as CA_i. It is the task of the experts to identify clusters by unambiguous assignment of production operations, with respect to their values in all identified change barriers. The design step separates what is impossible to be produced on a same process module, with the boundaries set by the most universal, conceivable solution (Step 2). This also means that all production operations assigned to one cluster share the same process module architecture, as defined by the function-object model (Section 5.1.1.3). It is quite certain that there are several relevant change barriers for the clustering. To facilitate the clustering totally independent groups of operations should be sorted first, before iteratively splitting the processes.

The clustering is a business-knowledge-intensive process. Not only must the conceivable solutions and their limitations of application be known, but there may be several possible solutions. Considering an example of operations, quantified by two different change barriers, and four solutions S1 to S4, overlapping ranges of solution validity may be possible (Figure 6.4). In consideration of Corollary 2, to minimize the number of FR_i, and Corollary 6, to achieve large design ranges, the maxim to design upon is to maximize each cluster, both by the number of clustered production operations as well as by the spread covered by a solution. In the given example (Figure 6.4), S2 should define the first cluster, as it embraces the highest number of production operations and accounts for the highest spread of design range in regard to the first change barrier of the example. An S3-defined second cluster is still needed, as there are production operations, that S2 cannot execute. S4 delivers a conceivable solution that covers all production operations in the dimension of the second change barrier of the example. Thus, a further separation of the two identified clusters of the example is not necessary.

A clear allocation of production operations to CA_i follows, thereby defining the clusters of operations (Equation 6.1). The allocation is straightforward for those operations that are inside of the range of only one of the solution options. For operations within overlapping solution ranges, a decision needs to be made. In the given example (Figure 6.4), this accounts for the operations op9 to op12. According to Corollary 2 and Corollary 6, they are assigned to the S2-defined cluster. This decision leads to a decoupling of an otherwise coupled design (Corollary 1), as it results in disjunct clusters.

[123] As change barriers and their quantification are inherent attributes of a system, it may be possible that some barriers found are not relevant to all production operations. In this case, they are simply marked as not valued (NV) for that operation.

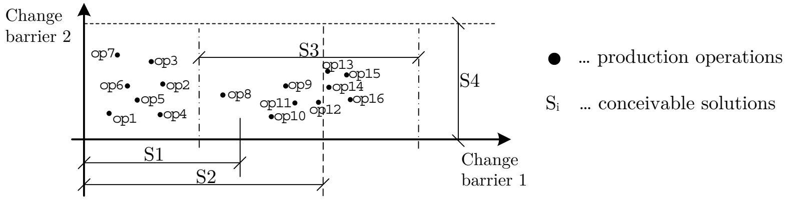


Figure 6.4: Comparison of production operations and conceivable process solutions

$$CA_{1(S2,S4)} = \{op1, op2, ..., op12\} \qquad CA_{2(S3,S4)} = \{op13, ..., op16\} \tag{6.1}$$

A review of possible solutions may alternatively lead to the identification or the design of new conceivable solutions that are able to cover the complete solutions range of previously separated solutions (Corollary 7).

The specification of a CA_i according to conceivable solutions does not mean that an identified conceivable solution is necessarily implemented in the subsequent design. There might be design constraints that motivate designers to pursue alternative process module designs which can even mean to split foremost clusters. The according iterations of the design process are initiated by the overall system design and evaluation (Section 6.2) and are to be ignored in this early function-oriented design phase.

As input, the list of identified operations (Step 1) as well as the list of identified change barriers (Step 2) are needed. Additionally, expert knowledge and business understanding is crucial, to evaluate the relevance of each change barrier per production operation.

The results are value-add-related, disjunct CA_i as clusters of production operations.

Step 4: Derive possible intralogistic material flow operations.

From a purely functional perspective, a transport to another PM instance is possible after any executed operation (Section 5.1.4). To derive possible material flow operations, the value-add operations are analyzed for their logistics-relevant output state after process execution. The material flow operations are specified according to this output state.

In an instantiated production system, not all of the identified material flow operations need to be executed. The aspired universality of value-add process modules incentivizes to perform as many successive value-add operations in one go on the same process module. Nevertheless, all theoretically possible material flow operations are considered in this step, to not constrain the system segmentation by logistics.

As input, the list of value-add operations (Step 1) is taken.

The result is the list of possible material flow operations.

Step 5: Identify change barriers of material flow operations.

The design should strive for universality in material flow process modules (Corollary 2). Again, technical, technological, and organizational restrictions may prevent the integration of all material flow operations onto one type of material flow process module. Similar to the approach of clustering operations of manufacturing and assembly, the respective material flow change barriers need to be analyzed. For that matter, logistic relevant states of produced parts and subassemblies are derived from the list of intralogistic material flow operations (Step 4). Very often, the shape of parts and subassemblies force a split, as a damage-free transportation needs a respective form-locking fixture. The function-object model of material flow processes (Figure 5.8) serves as a framework to guide the identification of change barriers, when addressing the guiding questions:

- *Is a solution conceivable that enables to transport all produced parts and subassemblies of the product state reached through the value-add operations (Step 1) on an identical material flow process module?*
- *If not, what is the criterion that forces the split?*

As input, the list of possible material flow operations (Step 4) and expert knowledge about potential technological, technical, and organizational implementations of the material flow operations and their boundaries, as well as the function-object model of material flow processes, are needed.

The result is a list of relevant change barriers with a focus on the material flow process.

Step 6: Cluster material flow operations to according CA.

Similar to the clustering of value-add operations, clusters of the material flow processes need to be built. In analogy to the process described for the value-add operations (Step 3), cluster are derived, and an unambiguous assignment of material flow operations to the clusters follows.

As input, the list of material flow operations (Step 4) and the list of material flow relevant change barriers (Step 5) are needed, together with the business understanding of the expert team.

The results are material flow-related, disjunct CA_i, as clusters of operations.

Step 7: Reflect on potential future operations.

The hitherto defined CA merely reflects a known product spectrum which has been used as a representative for the process module design goal clarification. This seventh step aims to expand CA with (predictable) future developments. It is a forethought of a possible change of FR, to enable an easier adaptation of the system. As the modularity of the system allows for later integration or substitution of process modules, an immediate instantiation of respectively needed future system functions is not necessary.

Operations are not directly associated to specific products in the previous steps of this functions-oriented planning phase. Consequently, a prediction of future developments should not to be carried out as a discussion of potential future products, either. Moreover, a potential future development of value-add and material flow process requirements must be discussed.

Several state of the art methods may be used by the expert design team for a prediction of the future development. Scenario technique and the technology-calendar approach have been applied for the design of changeable production systems[124]. Prediction must be executed in two dimensions:

1. a forecast of the development of current processes within the given change barriers
2. addition of desired or anticipated processes by scenarios of disruptive developments

Together, this results in an extension of the spread of operations within already identified clusters and possibly the definition of new clusters as additional CA_i. Furthermore, previous CA_i need to be re-evaluated eventually with respect to newly identified change barriers.

As input, strategic objectives of the manufacturer as well as change-driver-relevant market and innovation trends of technical and technological developments should be prepared.

The result is the final CA for the consecutive system design.

Step 8: Map FR to CA.

Each CA_i has to be translated into one CEME FR_i. Every FR_i represents the topmost level of functional process requirements of operations, to be executed by a respective process module. The CA-FR mapping is associated with desired usage ranges for FR_i specification, that reflect changeability requirements and permissible tolerances of the cluster's operations (Section 5.1.2).

The reference model introduced flexible design range (fdr) and flexible design points (fdp), and reconfigurable design range (rdr) and reconfigurable design points (rdp), to quantify changeability requirements, and the design ranges dr_{is} and dr_{future} to quantify permissible tolerances. Sets of flexible and reconfigurable design points (FDP, RDP), and the boundaries of the design ranges, are specified by change barrier quantification. There must be a design range, or set of design points, per change barrier.

Ranges of fdr and rdr are spanned between the lower and upper values of the change barrier parameter of all associated production operations, for each FR_i. When overlapping,

[124]Hernández (2003) introduces scenario technique. Löffler (2011) applies the technology-calender. (Section 3.1.2.2)

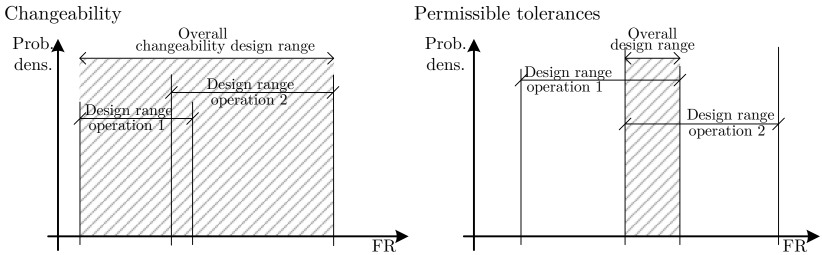


Figure 6.5: Derivation of FR design ranges

the overall changebility design ranges are spanned between the minimum and the maximum of the overlap (Figure 6.5, left).

Similar to the specification of changeability requirements, permissible tolerances associated to a CA_i are derived from the respective production operations. Their overall requirement is, however, determined by the most narrow overlap of tolerance ranges (Figure 6.5, right).

Other than conventional, flexibility and reconfigurability requirements can be associated with multiple discontiguous design ranges (Table 6.1). A combination of design ranges and design points outside of the ranges is also possible. In the case of no needed flexibility, the cardinality of the set of design points equals 1, i.e. only one design point is defined.

Flexibility and reconfigurability design ranges can be directly transformed to the changeability model of flexibility and change corridors (Figure 6.6). All needed production operations for the production of currently known and planned variants add to the flexibility and reconfigurability design ranges of the system design. Potential future operations are considered by a reconfigurable design range rdr and design points rdp.

6.1.2 Process module hierarchy (FR-DP)

The design goal clarification builds functional clusters for the process module design. To actually define a process module for each cluster, the required hierarchical structure of processes needs to be affirmed. A process-architecture is defined by an *FR-DP* mapping which effectively assures that all needed processes and activities are incorporated into a process module, to execute clustered operations of the associated CA_i. As a result of the *FR-DP* mapping, the hierarchical concept of the personalized production system is defined.

The reference model delivers a reference process hierarchy with the function-object models for manufacturing, assembly, and material flow (Figures 5.6, 5.7, 5.8). A function-object reference model must be selected from the classes of manufacturing, assembly,

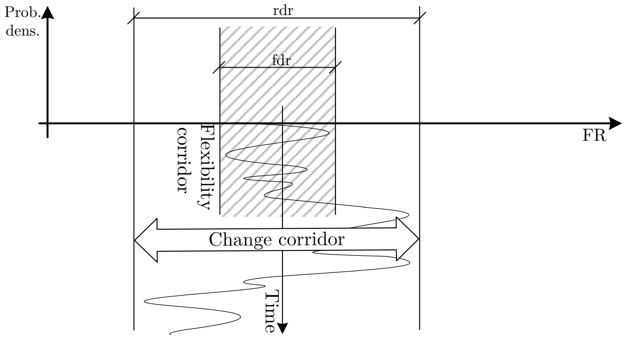


Figure 6.6: Flexibility and changeability corridor model (Figure 3.1) translated into AD systematic.

or material flow, and be assigned to the previously defined FR_i, to match the class of production operations clustered in the associated CA_i. The system designers need to review the selected model's *FR-DP* decomposition. It must be checked if the reference process hierarchy fits project-specific requirements on the subprocess activity levels, and the design needs to be checked for independence.

Functional necessities may require for a use case-specific adaption of the reference model, in order to tailor the process hierarchy to the needs of the previously determined design goals. It is the task of the designers to identify the inevitableness of an alteration and adapt the model accordingly. The function-object model needs to be adapted for three principal reasons:

1. **Operations-specific process requirements:** The characteristics of production operations, clustered in a CA_i, may alter the activity structure. It is possible that certain branches of the reference model's *FR-DP* decomposition hierarchy can be eliminated or duplicated, in parts or altogether.

   Example: A screwing process does not produce residue. The *eject residue* activity branch FR_{21n6} is deleted from the model (Figure 6.7, left).

2. **Coupled FRs:** The reference model states an ideal design for the *FR-DP* mapping on production system level. A FR_i may, however, be coupled due to technological constraints. In this case, a production operation cannot be successfully performed independent of a second operation of a different CA_j. The result is a lack of factory load case readiness of transportation between operations of CA_i and CA_j. With no feasibility of material flow between coupled processes, the respective process module instances cannot be separated spatially but need to be placed right next to each other

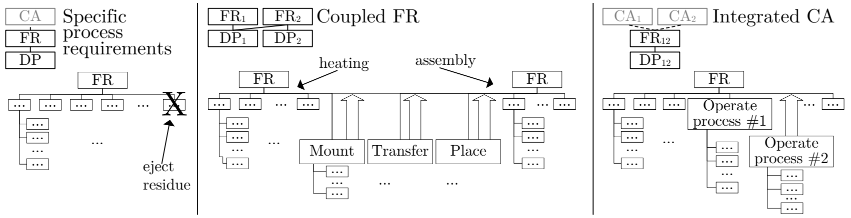


Figure 6.7: Example process module hierarchy adaption

in a layout with a direct transfer of goods between them. The functions-object model of the respective value-add processes need to be coupled and a material flow branch needs to be integrated into the decomposition hierarchy. If the cluster contains further production operations that do not need a direct coupling, the design trees need to be altered to additionally integrate sluices to feed in and eject parts between coupled process modules. There are two main reasons provoking such a coupling[125]:

- Process requirements: Deficient ability of part or subassembly of a CA_j to hold a certain precondition, achieved by a previous operation of a CA_i, during transport, such as tempering or cleaning.
- Part or subassembly conditions: Deficient ability to withstand deterioration of parts and subassemblies processed by an operation of CA_i, due to transport without finishing a subsequent operation assigned to a different CA_j.

Example: To execute a shrinking process, the processes of heating and assembly need to be executed immediately after each other. (Figure 6.7, middle).

3. **Integrated CA:** As an alternative to couple FR_i it is possible to iterate into the cluster definition and split the specific production operations into separate CA_i. This results in an ideal design, when an according FR_i integrates both the dependent operations. The *FR-DP* hierarchy needs to be functions-integrative, ultimately adapting the decomposition hierarchy with additional activity branches.

   Such a separation of CA_i potentially contradicts Corollary 6 to achieve largest design ranges. It is therefore only to be pursued if the resulting greater specialization of process modules for the execution of the separated operations is likely to lead to a better overall system design.

   The same alteration of the process hierarchy is needed, if operations of different technologies and processes are not split into separate CA_i. This often occurs for

[125] Potential solutions for material flow, to prevent the deficiencies, play a role when determining the coupling of the design. If a solution is conceivable that allows to keep FRs independent, the ideal design is to be kept at that functional stage of the design.

clusters of manual assembly operations, where the simplicity of tools and fixtures doesn't justify a separation, and, consequently, no change barriers are defined that would cause the split.

Examples: Integration of heating and assembly processes in one CA_i, to execute a complete assembly process by shrinkage in one integrated process module. A heating process must be added as a second value-add activity branch. (Figure 6.7, right).

As the functional scope of the system is in the focus of this design phase, an assembly-sequence-dependent coupling of production operations is not yet considered. An adaption of the process module hierarchy on activity level needs to be decided, based on a case-by-case analysis of all operations per cluster. To identify a coupling, the essential question is, whether or not each operation of a cluster CA_i can be executed independently, with the functions delivered by a CA_i-FR_i-DP_i mapping, and without having to utilize functions, that are delivered by another DP_j. To check on the independence of a design (Section 4.2.2), the following questions are to be addressed:

1. *Does the functional process scope given through DP_j affect the successful processing of any of the operations clustered in a CA_i?*
2. *Would failing to successfully execute the process of DP_j affect the successful processing of any of the operations clustered in a cluster CA_i?*

If both questions can be answered with a no, the design is independent. If one of the questions is answered yes, there is a coupling, and the process hierarchy as given by the functions-object reference model needs to be altered.

6.1.3 Process module functional configuration (DP-PV)

So far, the design process derived the design goals through a clustering of production operations and the specifications of their associated process requirements and defined the process hierarchies. However, no production system elements for process execution have yet been assigned. The *DP-PV* mapping finishes the functional pre-instantiation of process modules. The mapping assigns production system elements, thus defining the functional abilities of different process module configurations for each cluster of production operations.

Activity level PV_i are selected from a knowledge base of functions. An appropriate selection method and supporting calculations rules guide the selection process. Configuration embodiments are saved as functionally pre-instanced process modules in a knowledge base of process modules. They are kept available as process level PV_i for an actual instantiation process in the subsequent system design. The knowledge bases can be implemented as a relational database (Figure 6.8). The records of the knowledge bases correspond to the

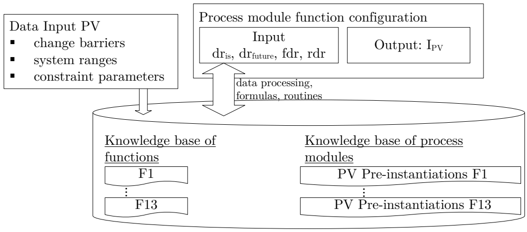


Figure 6.8: Knowledge base system for process module configuration

alternative AD solution candidates ($DP_i^a, DP_i^b, ..., DP_i^t$) of flexible systems (Equation 4.2, Section 4.2.3).

It is impossible to create a universally valid and complete collection of process modules, just as it is impossible to define generally valid change barriers. A process module configuration reflects the currently used production equipment of a manufacturer as well as the state of the art of market-available alternatives, fitting to the company framework and production strategy. Manufacturers need to create their own specific knowledge bases and continually add new functionally pre-instanced process module configurations to cover new developments, eventually provoking new change barriers.

There are two AD corollaries that are relevant to the process module configuration[126]:

- **Corollary 3**: *Integration of physical parts*
- **Corollary 4**: *Use of standardization*

6.1.3.1 Knowledge base of functions

Process module functions have been defined by the function-object reference model and mapped to reference production system elements (PV_i) by the object model. A knowledge base of functions has to be filled with possible production system solution elements per each reference function[127] (Table 5.1). An overall knowledge base, thus, consists of 13 knowledge sheets, each dedicated to a certain function, filled with records of alternative, functionally fitting PV_i (Figure 6.9).

For a sophisticated selection of PV_i, a comparison of PV_i system ranges with the requirements of changeability and permissible tolerances must be made possible. The data input into the knowledge base system of functions, therefore, describes the attributes of all PV_i by their flexibility potentials (flexible system range fsr, flexible system points fdp) and their actual process capability sr_{is} (Figure 6.9), as specified by the reference model

[126]The specific application of Corollary 3 and Corollary 4 is outlined in Section 6.1.3.3.

[127]Again, the effort to realize a overall valid, general knowledge base of all market-existent production solution elements would be too vast. As such, an instantiation of the knowledge base can only be done specifically for a manufacturing company, production system, or product spectrum.

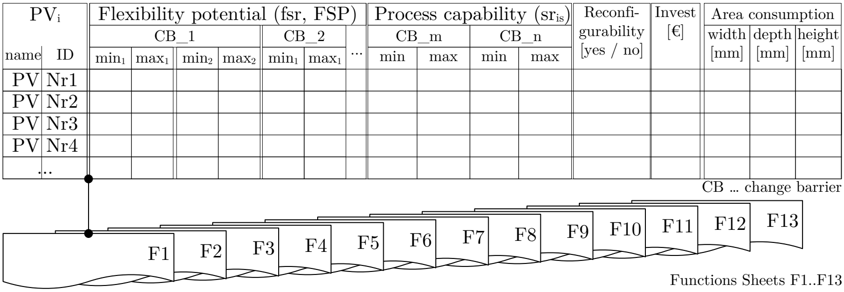


Figure 6.9: Structure and attributes of the knowledge base of functions

(Section 5.1.2). The flexibility potential of a PV_i reflects its universality and scalability, rated in the dimensions of the change barriers. The existence of a PV property of mobility, modularity or compatibility is indicated as another attribute of each PV_i record, which is the basis to judge on the reconfigurability potentials of the system[128] and possible future process capabilities (Section 6.1.3.2). Minimum and maximum system range values build the attributes of the PV_i records. If a system range consists of several discontinuous ranges, each range results in a new pair of attributes. To describe a system point, the maximum value is input as equal to the given minimum value. All PV_i system ranges are quantified in the dimensions of all the change barriers. If change barriers or multiple ranges are irrelevant to certain functions or PV_i, according attribute fields are filled with not valued (NV).

To enable an overall system evaluation in regard to the input constraints, the constraint parameters Area and Invest are also a data input into the database system of each PV_i record. Area represents the consumed area of a PV_i instance and is specified by the attributes of width, depth and height. Invest specifies the investment cost of a PV_i.

A unique ID makes the PV_i accessible for the process module configuration process.

6.1.3.2 Evaluation method for PV selection

Axiomatic Design (AD) selects the one solution out of different alternatives that is best suited to successfully satisfy given permissible tolerance requirements (Section 4.2.3). The adapted calculation rule for the evaluation of flexible systems (Equation 4.6, Section 4.2.3) is suitable to compare solutions by their success probability to satisfy a spread of design requirements.

[128] Universality and scalability are inherent characteristics of a flexible system. Mobility, modularity and compatibility enable the reconfiguration of a system. (Section 3.1.1.3)

The CA of the personalized production system design usually contain multiple production operations per CA_i (Section 6.1.1). Accordingly, production system elements (PV_i), such as the design solutions for process module design, must be flexible towards a spread of change barrier parameters from the contained production operations (Figure 6.5). PV_i must also cover the specific tolerance requirements of all contained production operations. Hence, there are two dimensions to compare PV_i for selection: First, a PV_i's changeability in respect to the required product variety. Second, its suitability to fulfill an admissible process deviation. The overall information content I of both evaluation dimensions is achieved by summary (Equation 6.2):

$$I_{Overall} = I_{changeability} + I_{process-capability} \tag{6.2}$$

To calculate $I_{changeability}$, the calculation rules for flexible systems are used as a basis (Equation 4.6, Section 4.2.3). To judge on a PV_i's suitability to keep a process deviation within given tolerances, $I_{process-capability}$ is determined applying AD's original equations for the calculation of the information content (Equations 4.3 to 4.5, Section 4.2.3). An extension of both evaluation schemes is needed to cover for the two aspects of changeability, i.e. flexibility and reconfigurability and for current and future process capability requirements, as defined by the system and design ranges given by the reference model (Section 5.1.2).

Evaluation dimension changeability

The information content I is computed separately for flexibility and reconfigurability (Equations 6.3), for each individual change barrier relevant to one PV_i. As each FR_i is usually characterized by multiple change barriers, a two-dimensional model (Figure 3.1) does not suffice: the overall $I_{Flex,k}$ and $I_{Reconfig,k}$ are the sum of all m I_k (Equations 6.4), where $k = 1, ..., m$ represent m change barriers, summed up for all PV_i.

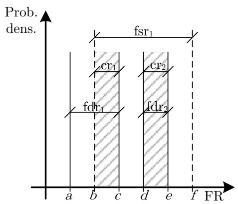
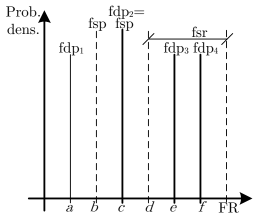
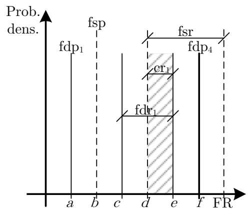
$$I_{flex} = log_2\left(\frac{1}{p_{flex}}\right), \quad I_{reconfig} = log_2\left(\frac{1}{p_{reconfig}}\right) \tag{6.3}$$

$$I_{flex} = \sum_{i=1}^{n}\sum_{k=1}^{m} I_{flex,k,i}, \quad I_{reconfig} = \sum_{i=1}^{n}\sum_{k=1}^{m} I_{reconfig,k,i} \tag{6.4}$$

The flexibility and reconfigurability components are summarized to $I_{changeability}$ (Equation 6.5).

$$I_{changeability} = I_{flex} + I_{reconfig} \tag{6.5}$$

To obey Axiom 2, the smaller $I_{changeability}$, the better. If a design solution can cover the required flexibility and reconfigurability completely, it follows $I_{changeability} = 0$.

a) Multiple design ranges	**b) Multiple design points**	**c) Combination of design ranges and points**
		
$fdr = \bigcup_{i=1}^{n} fdr_i$ $p_{flex} = \frac{\sum_{i=1}^{n} \lvert cr_i \rvert}{\sum_{i=1}^{m} \lvert fdr_i \rvert}$ for i,m,n $\in \mathbb{N}$	$FDP = \{a, b, ..., n\}$ $p_{flex} = \frac{\lvert \{cp_i, ..., cp_n\} \rvert}{\lvert \{fdp_i, ..., fdp_m\} \rvert}$	$fdr = \bigcup_{i=1}^{n} fdr_i$ $p_{flex} = \frac{\sum_{i=1}^{n} \lvert cr_i \rvert}{\sum_{i=1}^{m} \lvert fdr_i \rvert}$ for i,m,n $\in \mathbb{N}$; compare a)
Example: $\lvert cr_1 \rvert = \lvert c - b \rvert = 1$ $\lvert cr_2 \rvert = \lvert e - d \rvert = 1$ $\lvert fdr_1 \rvert = \lvert c - a \rvert = 2$ $\lvert fdr_2 \rvert = \lvert e - d \rvert = 1$ $p_{flex} = \frac{1+1}{2+1} = \frac{2}{3} = 66\%$	Example: $CP = \{fdp_2; fdp_3; fdp_4\}$ $\lvert CP \rvert = 3$ $FDP = \{fdp_1; ...; fdp_4\}$ $\lvert FDP \rvert = 4$ $p_{flex} = \frac{3}{4} = 75\%$	Example: $\lvert cr_1 \rvert = \lvert e - d \rvert = 1$* $\lvert fdr_1 \rvert = \lvert e - c \rvert = 2$ $p_{flex} = \frac{1}{2} = 50\%$ *FDP ignored due to fdr

fdr ...flexible design range; fsr ...flexible system range; cr ...common range; fdp ...flexible design point; fsp ...flexible system point; FDP ... set of flexible design points; CP ...set of common points; p_{flex} ...success probability regarding flexibility

Table 6.1: Calculation rules for p_{flex} with multiple design ranges and design points

The design and system ranges for the evaluation are quantified in the CA-FR mapping. The assessment of a design's success probability in the context of changeability evaluation needs to consider multiple design and system points and multiple discontiguous design and system ranges. There are three possibilities:

- multiple design ranges (Table 6.1, left)
- a set of multiple design points (Table 6.1, middle)
- a combination of design points and ranges (Table 6.1, right)

A common range cr exists whenever there is an overlap between a system and a design range. It is irrelevant whether this overlap is caused by one or multiple design or system ranges. In discrete cases, a set of singular points replaces the ranges. In the case of no needed flexibility, the cardinality of such a set equals 1.

A set of common points CP is built by all flexible design points fdp that are either overlapped by a flexible system range fsr or share the same value with a flexible system point fsp.

$I \to \infty$, if a set of system points is selected to map one or several design ranges: The number of points in a steady range outnumber any number of discrete points by far. For the same reason, sets of flexible design points FDP and reconfigurable design points RDP may be ignored if there is also a design range required for the same change barrier. The calculation logic for such a combination of design ranges and points reduces to the logic of design ranges without design points. If the ignored design points are of great importance to the success of a design, the design ranges of the change barrier need to be replaced by a set of flexible design points FDP or a set of reconfigurable design points RDP. The replacement enables the calculation of the sucess probability p in the logic of a multiple design points design, however puts disproportional importance on the design points.

Common points and common range (cp, cr) can also be calculated independently of each other and summarized.

All equations are deliberately given for the case of a uniform distribution of design range values: Due to the functional scope of the process module design, all product variants are treated as equal. Uneven production volume distribution is not considered until the instantiation of process modules (Chapter 6.2).

Equations for the calculation of the success probability of a design regarding flexibility p_{flex} (Table 6.1) are equally valid for the assessment regarding reconfigurability $p_{reconfig}$. Flexible system points fsp and flexible system ranges fsr may be directly retrieved from the knowledge base of functions (Section 6.1.3.1). With the property of mobility, modulary and compatibility, likewise included as an PV_i attribute in the knowledge base, it is possible to value (sets of) reconfigurable system points (rsp, RSP) (Figure 6.10):

- If a system can be replaced easily without reconstruction of the supersystem, it follows a reconfigurable system range rsr= Ω. Ω stands for the universal set of all same function systems available on the market.
  Example: A worker at a manual workstations can be replaced by a newly hired worker with different skills without having to change the setup of the workstation itself.
- If the system itself contains exchangeable subsystems, it follows rsr=$\mathrm{rsr}_{subsystem}$.
  Example: An industrial robot, permanently installed within workstations, providing an exchangeable robot arm to adapt its reach.

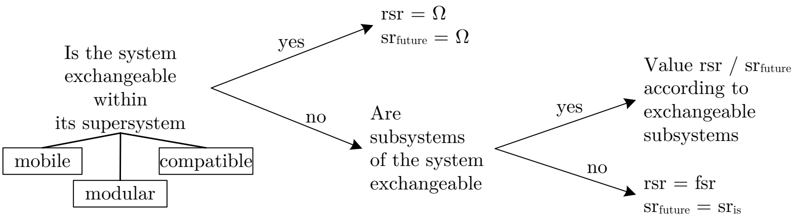


Figure 6.10: Decision tree to quantify rsr and sr_{future}

- If neither of the above applies, the system does not provide further reconfigurability than its current (flexible) setup. Reconfigurable and flexible system range are equivalent: rsr=fsr.

So far, a surplus of flexibility is not assessed as I_{flex} and $I_{reconfig}$ rightly compare against limited requirements. A surplus holds opportunities, as the future needs are built on possibly incorrect scenarios. As functions-oriented selection rule, the one solution with the highest cardinality of flexible and reconfigurable system range (fsr, rsr) should be chosen from two equally suitable PV_i.

Evaluation dimension permissible process deviation

Contrary to the evaluation of changeability, disperse system ranges occur in the case of tolerated process deviations. The calculation rules of AD's Axiom 2 (Equations 4.3 to 4.5) are applied.

The PV-inherent precision is expressed as system range sr_{is}, and the permissible process deviation is expressed as design range dr_{is} (Section 5.1.2.2).

The evaluation of sr_{future} matches with the evaluation of the reconfigurable system range rsr (Figure 6.10): If the precision-defining system is reconfigurable within its supersystem, i.e. if mobility, modularity, or compatibility are given characteristics of a selected PV_i, it follows $sr_{future} = \Omega$. Ω stands again for the universal set of all same function systems available on the market. Exchangeable subsystems, alternatively, lead to $sr_{future} = sr_{future,subsystems}$. If a system is neither reconfigurable within its supersystem, nor is it built from reconfigurable subsystems, it follows $sr_{future} = sr_{is}$.

The actual and future components are summarized to $I_{process-capability}$ (Equation 6.6).

$$I_{process-capability} = I_{is} + I_{future} \tag{6.6}$$

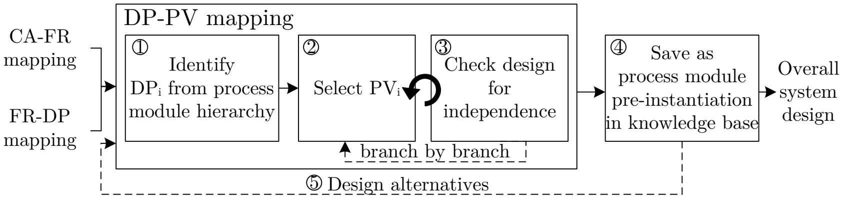


Figure 6.11: Process module configuration process

6.1.3.3 Process module configuration process

The process module configuration needs to assign a production system element to each process activity. The configuration is a *DP-PV* mapping. The following steps apply (Figure 6.11):

1. **Identify DP$_i$ from the process module hierarchy:** At least one process module pre-instantiation needs to be configured for each CA$_i$. All activity DP$_i$, to be assigned with PV$_i$, are given by the process module hierarchy which was previously selected and adapted in the *FR-DP* mapping. The according design ranges are available through the previous *CA-FR* mapping.

2. **PV selection:** Process modules are configured out of the knowledge base of functions through an attribute selection of PV$_i$. A PV$_i$ is selected for every lowest level leaf of the *DP* decomposition. Each leaf represents an activity. The selection designs each process module branch by branch. All activities of one branch of the design hierarchy need to be selected, before proceeding to the next step.

   The evaluation method for PV$_i$ selection needs to be applied. Generally, the PV$_i$ delivering the lowest $I_{overall}$, to satisfy the design ranges of a DP$_i$, should be mapped to this DP$_i$. To apply standardization (Corollary 4), same PV$_i$ should be selected for the same activities of different process module configurations, whenever possible. This reduces the diversity of process module elements instantiated in a production system, making the system less complex for planning, purchasing, and maintenance, and easier to control for the operators. To integrate physical parts (Corollary 3), it is furthermore desirable to select same PV$_i$ for same functions in different branches of one process module hierarchy.

3. **Check for independence:** Functional independence is the key to a good design. The process module design needs to be checked for independence. In the prevalent case of functional process module configuration, the functions-object model of the reference model, and also its adapted *FR-DP* process module hierarchy are given

as an ideal design on the activity level. The selection of PV_i might violate this independence. The system designer needs to write the *DP-PV* design matrices after the configuration of each branch and after the complete configuration of a process module, to analyze the design for independence.

If independence cannot be achieved, a coupled design needs rework by alteration of selected PV_i. A decoupled design is an indicator for interdependent system ranges. Due to a coupling of e.g. an assembly tool and the assembly manipulator, the working load flexibility and reconfigurability system ranges (fsr, rsr) of the manipulator needs to be reduced by the weight of assembly device and tool. The dependencies must be analyzed and the system ranges of the corresponding PV_i must be re-valued within the configuration.

4. **Knowledge base of process modules:** Each configuration results in a functionally pre-instanced process module. It must be saved for subsequent system designs as a PV_i record in a knowledge base of process modules, described by its overall system ranges and overall system parameters with an influence on the design constraints.

   A complete system is only as capable as its subsystems. The system ranges of a configured process module can ultimately only be judged upon, once the configuration is complete. The overall system ranges of flexibility fsr, reconfigurability rsr, and process ability sr_{is} and sr_{future} are valued for all identified change barriers. Irrelevant change barriers are marked not valued (NV). For relevant change barriers, only the overlap of all PV_i system ranges in the dimension of this change barrier count (Figure 6.12). If no common system range exists, selected PV_i are incompatible and need to be replaced within the configuration until an overlap is achieved.

   Example: If the change barrier of part width was given as $fdr_{width} = [5mm; 300mm]$, the selected gripper system device offers $fsr_{gripper} = [150mm; 300mm]$, but a jig was selected with $fsr_{jig} = [5mm; 100mm]$, then there is no common flexible system range and either the jig or gripper system need to be exchanged.

5. **Alternative designs** An iteration of the configuration process creates different process module pre-instantations of the same CAi. They offer the same functional scope, albeit with different design. Different designs are possible, as there is potentially more than one satisfiable solution, e.g. manual versus automated PV_i, or PV_i of technological progress potentially not yet fully implementable for the complete production system. Furthermore, two equally suitable solutions may differ in their surplus on flexibility or reconfigurability, impacting the system parameters[129]. At

[129]The economical impact of a PV_i selection is neglected in this functional design phase. It will be considered in the overall system design (Section 6.2.4), relative to design constraints.

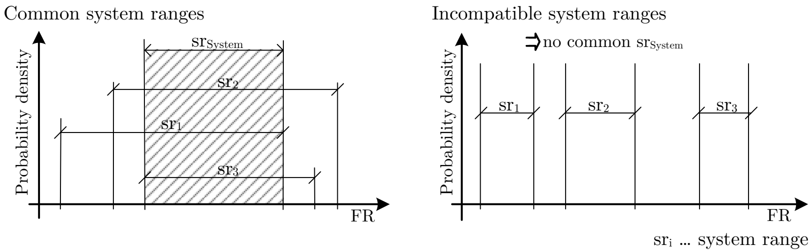


Figure 6.12: Derivation of process module system ranges

this stage of the design process, alternative designs are desirable to provide the succeeding design phase of overall system design a larger knowledge base of process module pre-instantiations to select from.

6.2 Production system design

The actual production system is designed through an instantiation and relation of functionally pre-instanced process modules. The design determines the functional, hierarchical and structural concept of the production system. As preliminary step to the instantiation, the design-relevant production program needs to be prepared, and further design constraints must be clarified (Section 6.2.1). The following section is organized according to the independent or sequentially-dependent design tasks for production system design (Figure 6.13).

The description of the value-add process module instantiation (Section 6.2.2) is followed by an explanation on how to achieve their physical and logical relation, which includes the integration of all system concepts in an ideal system layout (Section 6.2.3). Finally, an evaluation systematic of the personalized production system design embodiments is developed, to reveal the degree of achievement regarding input constraints of the design (Section 6.2.4).

6.2.1 Production program preparation

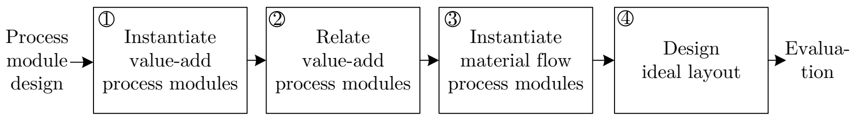


Figure 6.13: Production system design process

While process module pre-instances are designed for a general product spectrum of a manufacturer, the design of an actual production system must always consider an actual production system design project. Albeit the system must be designed reconfigurable, to equip it for future developments in a volatile business ecosystem, only under consideration of an actual or planned production program, a functionally and capacity-wise tailored system can be achieved. This is a precondition for a highly productive system, as demanded by the general objectives of a personalized production system (Section 1.1). Furthermore, input constraints and evaluation KPI, beyond those specified by the reference model, need to be delivered.

6.2.1.1 Product variants and scenarios of output volumes

The relevant information from the production program for the production system design are products and product variants as well as the production volumes of all variants. Through the specification of volume per variant the overall mix of variants (per specified time span, e.g., yearly) is also defined. A certain sequence of variants in the variant mix should not be specified, as the production system should be product mix flexible for an arbitrary mix of variants.

Variants and volumes may be given in different scenarios. Scenarios are made to reflect current flexibility requirements, as well as potential future reconfiguration needs. Future product scenarios may contain virtual variants and product concepts from early product development phases to reflect potential future developments.

6.2.1.2 Production operations and processing times

All production operations, including preparation and post-processing production operations, must be extracted from the list of product variants. The extraction must be a complete list of all needed operations, to manufacture or assemble any possible product configuration. An actual product configuration is thereby irrelevant. Appropriate material flow operations must equally be defined, to theoretically enable a transportation after each accomplished production operation. Each operation must be quantified by its system ranges in the dimensions of the change barriers, that have been identified during process module design.

For the capacity harmonization of the system, each operation's processing time PT per unit is a necessary input factor. If it takes too much effort to obtain the PT of each variant, the systematic of a standard variant with addition or deduction factors for variant configurations may be used (Figure 6.14)[130].

For the process module instantiation it is, furthermore, important to quantify the options of each production operation by their possible minimum and maximum amount in

[130]The values given in Figure 6.14 are examples from an industrial use-case of servomotor configuration.

Production operation	Basic Variant PT [min]	Configuration addition						
		Break [min]	Prop. [%]	Inerter [min]	Prop. [%]	Feather key [min]	Prop. [%]	... [min]
Heating	3	+ 30	20%	+ 90	2,5%	0	48%	
Pressing rotor pack	1,1	+ 1	20%	+ 0,3	2,5%	0	48%	
Balance shaft	1,95	+ 0,75	20%	+ 1	2,5%	+ 0,17	48%	
...								

Figure 6.14: Systematic of PT analysis with basic variant and configuration factors

a configuration. If there are variants that can be built without a specific operation, this operation's minimum amount equals zero. The maximum amount equals the maximum number that a specific operation may occur, due to the maximum amount of a configuration.

6.2.1.3 Precedence graph and precedence matrix

The product architecture of produced variants restricts the SOO. The designer must know sequence restrictions and freedoms for the layout design. The dependencies are prepared as precedence matrix and precedence graph for the all variants in the production plan. All possible configurations are unified in a max-configuration matrix and graph (Figure 6.15). The precedence graph is a directed graph. Each vertex represents a production operation. The edges between two vertices represent the sequence restriction. For standardization, the exemplary max-configuration graph positions production operations in the earliest possible segment. Isolated vertices are possible.

The matrix notation lists production operations symmetrical in row and column. A matrix element $a_{i,j} = 1$ reads as: *operation i must be finished before operation j starts*, where $i, j =\in \mathbb{N}$, for i rows and j columns. If the matrix elements equals 0, operation i and operation j are located in parallel paths of the precedence. They can be processed independently of each other.

Even though reflows are possible within a matrix production system, a main flow orientation should be pursued to achieve a standardized and transparent production operation. A known precedence logic is an important basis for the derivation of a SCC and the design of a flow-oriented layout. The precedence matrix is used for the segmentation of the production operations by the precedence logic. For each operation, the sum of successive and preceding operations can be calculated by summing up all a_{ij} per row and column (Equation 6.7).

$$\sum Successors(i) = \sum_{j=1}^{n} a_{ij}; \qquad \sum Predeccesors(j) = \sum_{i=1}^{n} a_{ij} \tag{6.7}$$

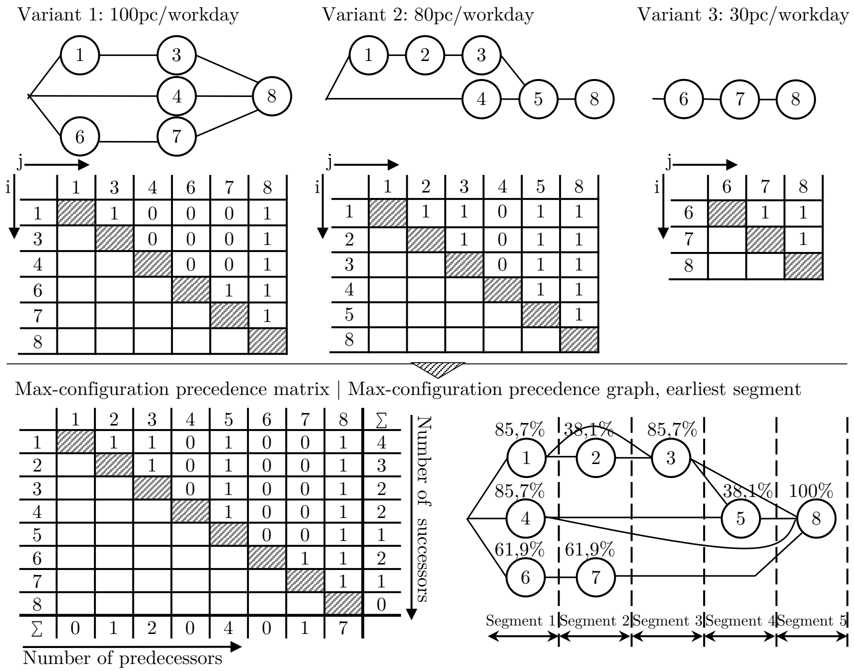


Figure 6.15: Max-configuration precedence matrix and precedence graph

Number of predecessors	0	1	2	4	7
production operations	op1 op4 op6	op2 op7	op3	op5	op8
Segments	1	2	3	4	5

op ...production operation

Number of successors	4	3	2	1	0
production operations	op1	op2	op3 op4 op6	op5 op7	op8
Segments	1	2	3	4	5

Figure 6.16: Determination of segments of the precedence sequence

The overall number of precedence segments equals the longest sequence of coupled operations. Operations are sorted ascending, according to the number of predecessors, and descending, according the number of successors (Figure 6.16). The segment of predecessors tells the earliest logical start of an operation. The segment according to successors tells its latest finish.

If an operation is assigned to the same segment according to number of predecessors and successors, it is part of a longest sequence and cannot be moved between segments.

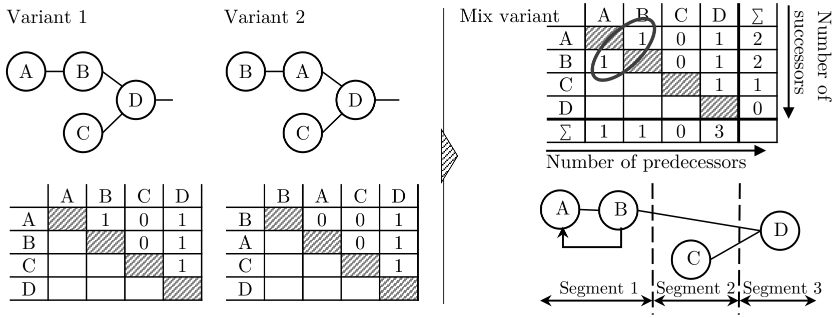


Figure 6.17: Max-configuration precedence graph with loops

This is the case for the production operations op1, op2, op3, op5 and op8 of the example (Figure 6.16). If the number of predecessors and successors delivers a different segment, a production operation can be moved between segments. In the example, this accounts for production operations op4, o6, op7. In that case, the earliest segment is the segment of the direct predecessor. The latest possible segment is the segment of the immediate successor.

If there are no contradictory precedence relations of production operations between different variants, the max-configuration precedence matrix transfers into a triangular form by sorting of operations. Loops in the max-configuration precedence graph occur due to contradictory couplings of successive production operations. They lead to a non-triangular precedence matrix (Figure 6.17). The example (Figure 6.17) shows the contradictory precedence between operation A and operation B. Production operations of contradictory precedence must be placed in one segment of the precedence logic.

6.2.1.4 Input constraints and further evaluation KPI

The generic model already defined the general input constraints to maximize changeability and to maximize productivity, as well as appropriate KPIs (Section 5.1). Further input constraints and evaluation KPIs for the system design may apply. These are usually defined by the management, and reflect company-valid operative targets, strategic decisions such as a commitment to a certain robot type for process manipulation, or project-specific bounds such as acceptable investment cost, or a threshold of maximum available area. The definition of input constraints also implies the specification of superordinate, process-independent changeability requirements, such as the capability for a minimum number of different variants to be processed on any given process module.

6.2.2 Process module instantiation

To instantiate the value-add process modules of the system, functionally pre-instanced PV_i are selected from the knowledge base of process modules. The process-oriented design approach selects process modules by function first, before considering capacity needs in the second step. A capacity harmonization between functionally differing PV_i defines the number of process modules (PM) for a certain production program. The relation of PMs establishes the process structure of the production system.

6.2.2.1 Value-add process module selection

The process module selection is a mapping of functionally pre-instanced PV_i with production operations. A decision for a PV_i has to be taken individually for each operation, in consideration of the operation's process requirements. The decision process is guided by AD's Axiom 2 and Corollary 3:

- **Corollary 3**: *Integration of physical parts.*

For the selection, all value-add operations, as derived in the production program preparation, are compared to all available PV_i from the knowledge base of process modules (Section 6.1.3.3). A tabular display is used for the comparison (Figure 6.18), highlighting the degree of automation of every PV_i as an important differentiator.

The cells of the table contain the information content I_i of each pairing. I is calculated on the basis of the change barriers and summed up (Equations 6.2 and 6.3 to 6.6). Actual tolerance and flexibility requirements (design ranges dr_{is}, fdr) are derived from the actual or planned production program. Future tolerance and reconfigurability requirements (design ranges dr_{future}, rdr) are taken from a future scenario, prepared in the production program preparation. For the assignment of PV_i to production operations, I_{flex} and $I_{reconfig}$ can either be $I = 0$ or $I \to \infty$, as the pre-instanced process module either delivers the flexibility capability to process this one operation, or not. $I_{process-capability}$ may be $0 \leq I \leq \infty$, depending on given tolerances.

According to Axiom 2, any production operation should be assigned to a PV_i, for which the mapping results in the smallest information content I_i. At the same time, the validity of Corollary 3 reduces the total number of different PV_i in the production system. For an integration of different operations into one process module the system designer should select the most universal PV_i. In the given example (Figure 6.18), PV_1, PV_3 and PV_8 are selected as most-universal functionally pre-instanced process modules to cover all listed production operations[131].

[131] The direct comparison of PV_3 and PV_5 shows, that both are able to execute operations op2 and op4. Even though operation op7 will most likely be executed on PV_8, as the mapping results in a smaller I,

value-add production operation \ process module pre-instance	PV_1	PV_2	PV_3	PV_4	PV_5	PV_6	PV_7	PV_8	PV_9	...
	man.	auto.	man.	man.	man.	man.	auto.	auto.	auto.	...
op 1	0	∞	∞	∞	∞	∞	∞	∞	∞	∞
op 2	∞	0	0	∞	0	∞	∞	∞	∞	∞
op 3	0	∞	∞	0	∞	∞	∞	∞	∞	∞
op 4	∞	∞	0	∞	0	∞	∞	∞	∞	∞
op 5	0	∞	∞	∞	∞	0	∞	∞	∞	∞
op 6	∞	∞	∞	∞	∞	∞	0	0	∞	∞
op 7	∞	∞	0,5	∞	∞	∞	∞	0	∞	∞
op 8	0	∞	∞	∞	∞	∞	∞	0	0	0

0; 0,5; ∞ ... Calculated information content of mapping of PV_i to a production operation (examples)

... Indication of smallest I for a mapping of PV_i to a production operation

... Indication of most universally applicable PV_i for listed production operations

Figure 6.18: PV selection table for value-add production operations

It is nevertheless possible, to deliberately select different PV_i for different operations, even though the same PV_i would be possible. Such a choice is reasonable if certain operations are automatable, but can also be executed manually, while other operations can only be executed manually. Automatable operations could, thus, be assigned with an automated PV_i, even though a selected manual PV_i would also be capable of their execution. Another reason is the unification of operations with non-configuration options on one process module. With the information on possible numbers of configuration options available from the production program preparation (Section 6.2.1.2), it is possible to instantiate process modules (PM) which are dedicated to only such operations that have a non-configuration option. Orders without such configuration omit these kind of PM altogether during operation, reducing the throughput time.

If there is still more than one PV_i equally suitable, after Axiom 2 and Corollary 3 have been applied, a decision should be taken by detailed comparison of the alternatives. Criteria are the degree of automation, the system parameters with effect on constraints and the surplus of flexibility and reconfigurability. A choice must be made, as the unambiguous assignment of production operations to PV_i reduces the complexity of production system operation.

It is possible to conclude the CA and FR of the production system design from this selection of PV_i (Equation 6.8). From the mapping of the production operations the FR-DP design matrices can be concluded (Equation 6.9).

$$CA_1 = \{op1, op3, op5\} \quad CA_2 = \{op2, op4\} \quad CA_3 = \{op6, op7, op8\} \tag{6.8}$$

PV_3 is judged to be more universal compared to PV_5 for its partial suitability to execute operation op7 (I=0,5).

$$\begin{Bmatrix} CA_1 \\ CA_2 \\ CA_3 \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} \qquad \begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP_1 \longrightarrow PV_1 \\ DP_3 \longrightarrow PV_3 \\ DP_8 \longrightarrow PV_8 \end{Bmatrix} \tag{6.9}$$

Only the change barrier-relevant requirements matter for the process module design. Other process requirements, linked to the production operations of each cluster, need to be analyzed before the subsequent step of value-add capacity harmonization. If the selected PV_i are not capable to fulfill those process requirements, the respective process requirement is either a new change barrier which has not yet been identified or a different, process-capable PV_i must be selected for the cluster. Both cases cause an iteration to previous design steps.

The process module configuration was done with reference operations derived from the actual and potential product spectrum of a manufacturer. If there is no suitable PV_i available for certain operations of the specific production system design, an iteration to process module design is necessary. The iteration may result in a functional extension of existing PV_i, the addition of new PV_i to the knowledge base of process modules, and even to the identification of new change barriers.

As a result of the process module selection, it is now clear which actual operations of the design use case are operated on each PV_i. A project-specific, detailed design of the selected PV_i must follow. A best-point arrangement of tools and equipment must be achieved to ensure a high productivity of manually-operated process modules. The detailed design arranges all elements of the PV in an actual PV layout. The design may be an individual work station or a number of workstations, in any arrangement. A classical U-cell arrangement of connected workstations is also possible. The detailed design of the PV_i must be finalized after the subsequent step of buffer dimensioning.

6.2.2.2 Value-add capacity harmonization

The capacity harmonization defines the number of instances of each previously selected, functionally pre-instanced process module. The instantiation of PV considers the overall capacity needs of a certain production scenario, as well as the distribution of capacity needs between different system functions. Capacity needs are derived from an average volume per defined period from the production plan. A volume variation within this time period is not considered for the capacity harmonization, and neither is a variant mix. This is sufficient for the production system design due to two reasons:

1. The dynamics of volume and variant spread are even harder to predict than an average needed volume. There would be a very high risk of using wrong plan numbers.

2. The layout paradigm of flexibly linked process modules has a high inherent variant mix flexibility. Variations of process times between different variants are buffered by the blank parts, base part and assembly parts buffers of the system (Section 5.1.3). The dynamic system behavior is, accordingly, considered for a sufficient buffer dimensioning (Section 6.2.3.6).

To decide on the number of instances per PV_i, the tabular display of functional suitability for process module selection is advanced (Figure 6.19). Capacity requirements of the design use case are calculated by multiplication of the average planned volume n_i with the PT_i of all i variants, for each production operations (Equation 6.10), and added into the harmonization table.

$$CapaNeed = \sum_i PT_i n_i \tag{6.10}$$

Production operations are listed as lines of the harmonization table. Functionally pre-instanced process modules (PV_i) are listed as the harmonization table's columns. They are assigned to each production operation, as specified by the PV_i selection. Each assignment of an operation to a process module instance adds to the utilization of this PM. Whenever a utilization reaches the target value (often set as 85% to cover OEE losses), a new instance of this respective process module PV_i must be added, and the capacity load is split equally between all same-function PMs[132].

In the given example (Figure 6.19), operation op8 could be executed on both PV_1 an PV_8 instances. For capacity reasons, the example allocates it at PV_8, resulting in a required number of PV_i instances of three PV_1, and one PV_3 and PV_8 respectively. PV_8 is not planned to be instanced more than once in the example, as the utilization is only an average value and the overall utilization of 100% is only exceeded by 2%. The average utilization must be validated regarding its dynamic behavior in the overall evaluation of the production system design embodiment (Section 6.2.4).

The harmonization table maintains the information about alternative, to the selected, PV_i. This enables iterations to PV_i selection, if an alternative assignment of production operations suggests the likeliness of a better harmonization.

The instantiation process results in a redundant design, as defined by the reference model (Section 5.1.3), if one process module instance per PV_i is capacity-wise not sufficient to satisfy all capacity requirements of the assigned production operations (Equation 6.11). The redundancy adds to the system's failure and routing flexibility (Section 3.1.1.1). As redundancy only occurs for PM instances, and the one-to-one *FR-DP-PV* mapping is kept, the redundant design of the personalized production system does not violate AD's independence Axiom 1 (Equation 6.12).

[132] The equal split of volumes between PMs is reconsidered for a flow-oriented line-up of PM (Section 6.2.3.1).

Volume: 210pc/workday		man.		auto.		man.		man.		man.		man.		auto		auto		auto		...	
		PV_1		PV_2		PV_3		PV_4		PV_5		PV_6		PV_7		PV_8		PV_9		PV_{10}	
value-add op	Vol %	PT	Capa need [min]	PT	Capa need [min]	PT	Capa need [min]	PT	Capa need [min]	PT	Capa need [min]	PT	Capa need [min]	PT	Capa need [min]	PT	Capa need [min]	PT	Capa need [min]	PT	Capa need [min]
op 1	85,7%	2	360	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
op 2	38,1%	–	–	1	80	1,5	120	–	–	1	80	–	–	–	–	–	–	–	–	–	–
op 3	85,7%	4	720	–	–	–	–	4	720	–	–	–	–	–	–	–	–	–	–	–	–
op 4	85,7%	–	–	–	–	1	180	–	–	1	180	–	–	–	–	–	–	–	–	–	–
op 5	38,1%	0,5	40	–	–	–	–	–	–	–	–	0,5	40	–	–	–	–	–	–	–	–
op 6	61,9%	–	–	–	–	–	–	–	–	–	–	–	–	1,5	195	1	130	–	–	–	–
op 7	61,9%	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	130	–	–	–	–
op 8	100%	~~0,8~~	~~168~~	–	–	–	–	–	–	–	–	–	–	–	–	0,8	168	0,5	105	1	210
Utilization		266%		19%		71,5%		171,5%		62%		9,5%		46%		102%		25%		50%	
Required no. PV_i instances		3				1										1					
Capacity/day		7h																			

[bold box] ... Indication of most universally applicable PV_i for listed production operations

Figure 6.19: Capacity harmonization table

$$\begin{Bmatrix} PV_1 \\ PV_3 \\ PV_8 \end{Bmatrix} = \begin{bmatrix} x & x & x & 0 & 0 \\ 0 & 0 & 0 & x & 0 \\ 0 & 0 & 0 & 0 & x \end{bmatrix} \begin{Bmatrix} PM_{1.1} \\ PM_{1.2} \\ PM_{1.3} \\ PM_3 \\ PM_8 \end{Bmatrix} \tag{6.11}$$

$$\begin{Bmatrix} CA_1 \\ CA_2 \\ CA_3 \end{Bmatrix} = \underbrace{\begin{bmatrix} x & 0 & 0 \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \begin{bmatrix} x & 0 & 0 \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \begin{bmatrix} x & x & x & 0 & 0 \\ 0 & 0 & 0 & x & 0 \\ 0 & 0 & 0 & 0 & x \end{bmatrix}}_{= \begin{bmatrix} x & x & x & 0 & 0 \\ 0 & 0 & 0 & x & 0 \\ 0 & 0 & 0 & 0 & x \end{bmatrix}} \begin{Bmatrix} PM_{1.1} \\ PM_{1.2} \\ PM_{1.3} \\ PM_3 \\ PM_8 \end{Bmatrix} \tag{6.12}$$

6.2.3 Process module relation

The generic reference model defines a layout of flexibly-linked process modules as the layout paradigm of personalized production (Section 5.1.4). The system inherent routing flexibility enables an ad-hoc re-sequencing of orders through the system. The logical and physical relation of value-add process modules (PMs) is, thus, not fixed by the matrix production system layout. However, the system design must facilitate an order sequence planning strategy that is capable to fully exploit the new optimization possibilities of order distribution and operation sequence planning (Section 2.1.4.2), and a material flow that is able to physically realize the flexible linkage of value-add PMs. Therefore, process module relation in the context of a matrix production system design does mean to lay the foundation for the process structure and a productive system operation. For the production system designer, this results in the following problems to define the logical relations:

- A theoretical assignment of operations to PMs, as a prerequisite for the layout-design, to achieve a process-oriented line-up of PMs during operation
- Conceptualization of an order and transport logic for the relation of PMs
- Selection of a strategy to handle disharmonized PMs

The following steps need to be realized to achieve the physical relation:

- Selection of material flow PV_i
- Selection of a material supply strategy
- Definition of a mean transport time
- Dimensioning of material flow elements and buffers

6.2.3.1 Process flow-oriented assignment of production operations to PM

Reflows are possible within a layout of flexibly linked process modules. A unidirectional material flow is, however, more transparent and requires less space for material routes. It is therefore desirable to arrange process modules as reflow-free as possible. To do so, all production operations are assigned to a process module instance (PM) to identify the main flow in the system.

The production program preparation (Section 6.2.1) sorts production operations into segments and derives the longest sequence of operations, under consideration of the operation-precedence logic. Initially, production operations are distributed equally to same-function PM (Figure 6.20). A main flow direction within the matrix production system is achievable, if production operations require PM in line with the precedence segmentation of the max-configuration precedence graph. The line-up of PM, as well as the SOO, must be sorted accordingly. In that case, a waterfall-shaped flow through the segments develops in the harmonization table (Figure 6.21). Considering the volume distribution of different production operations, it might be necessary to split operations between different segments in this theoretical operation assignment, to reflect differing SOO of different variants[133]. A direct flow between same-function PM is not acceptable, as any PM has to finish all possible production operations before an order leaves the respective PM.

[133] Compare production operation op3 in the example given by figures 6.20 and 6.21.

Vol:210pc/d

Seg.	op	Vol. %	Process Module Instances[min] $PM_{1,1}$	$PM_{1,2}$	$PM_{1,3}$	PM_3	PM_8
S1	op1	85,7%	120	120	120		
S2	op2	38,1%				120	
S3	op3	85,7%	240	240	240		
S4	op5	38,1%	13,3	13,3	13,3		
S5	op8	100%					168
	op4	85,7%				180	
	op6	61,9%					130
	op7	61,9%					130
Utilization:			88,9%	88,9%	88,9%	71,4%	102%
Capacity/workday:				7h			

Flow
Reflow

Figure 6.20: Assignment of production operations to PM

Vol:210pc/d

Seg.	op	Vol. %	Process Module Instances[min] $PM_{1,1}$	$PM_{1,2}$	PM_3	$PM_{1,3}$	PM_8
S1	op1	85,7%	180	180			
	op3	47,6%	199,9	199,9			
S2	op2	38,1%			120		
	op4	85,7%			180		
S3	op3	38,1%				320	
	op5	38,1%				40	
S5	op6	61,9%					130
	op7	61,9%					130
	op8	100%					168
Utilization:			90,5%	90,5%	71,4%	85,7%	102%
Capacity/workday:				7h			

Flow
Reflow

Figure 6.21: Process-oriented PM line-up

The number of different production operations per PM is made visible through the number of cells filled in the column of one module. Same-segment duplicated PMs are visible through the number of cells filled in the line of a production operation. Again, the distribution of the order volume is split equally between PM instances of the same PV_i within one segment.

This process flow-oriented assignment of production operations to process module instances PM is only of theoretical nature, reflecting the overall variant mix of the design project used as a basis to enable the subsequent definition of a productive and flexible layout. During the actual system operation, the order control strategy decides the route of a specific variant through the system. With the given routing flexibility, it is even possible for this decision to be taken ad-hoc. Whenever an order finishes its execution on a specific PM_i, it must be directed to a subsequent PM_j of a different function for further processing. An ad-hoc decision considers the current status of the system and respects specific logistical optimization criteria, such as order prioritization, throughput time or work in process (WIP) inventory. Each subsequent PM selection addresses order distribution and operation sequence planning (Section 2.1.4.2) of the process structure. The production system design must create a layout that facilitates these two new tasks of order sequence planning in the matrix production system.

The harmonization and process flow oriented assignment of PM may justify to have less-universal variants of a specific process module, essentially resulting in another PV specimen. Such configurations result in $I_{flex} > 0$, as they do not offer all processes and technologies required by the CA. A project-specific reduction of processes and equipment reduces investment and enables a better best-point positioning of material and tools. A later reconfiguration of such a process module with additional tools and processes, up to a complete reconversion into the original, universal PV_i, should be possible as the original process module hierarchy provided for it.

6.2.3.2 Capacity control strategy

The overall production system does not run on a balanced system cycle time. Nevertheless, it is desirable to achieve a harmonized distribution of process module utilization. In a highly harmonized system, the overall WIP in the systems' buffers is minimized and all PM operate simultaneously. The previous process module harmonization instantiated PV_is into PMs to prevent over-utilized value-add system elements. This process almost certainly results in some under-utilized PM instances. There are two options to deal with these disharmonizations, in order to achieve high productivity during operation:

1. **Multi-PM operation**: For manually operated PMs, a shared operator levels out disharmonized capacity distributions. The ultimate target of multi-PM operation is to achieve a high utilization and an even capacity distribution of operators. As an operator has to walk from one PM to the other, there are restrictions on the layout. Multi-PM operation is an excellent flexibility reserve, as a scale up of capacity is possible by adding operators and changing from multiple- to single-PM operation.
2. **Individual run times**: The flexible linkage enables the matrix production system to schedule individual run times of certain PMs, if several same-function PM exist in the system, or if certain PM are exclusively dedicated to specific, rarely required production operations. Due to the one-piece-flow concept, a potential temporary shutdown of PMs must be considered in the maximum-buffer capacity dimensioning of affected process modules. Furthermore, a flexible working time model or the introduction of job-hopper positions is needed to operate individual runtimes.

6.2.3.3 Selection of material flow PV and material supply strategy

The instantiation of value-add process modules (PMs) creates the prerequisites to derive the intralogistics material flow operations of the design use case. The overall number of actual material flow operations must be smaller than the number of value-add operations, as any value-add PM executes all possible value-add production operations before releasing an order for transportation (Section 6.2.3.4).

Similar to the value-add design process, material flow process modules are selected out of the knowledge base of process modules. By integrating as many material flow operations into a small number of different PV_i a high standardization of material flow equipment is achieved.

For the selection of material supply strategies, only a limited number of strategies qualify for a matrix production system:

1. Consumption-driven, material to value-add PM strategy (e.g. Kanban): eligible strategy for multiple-variants-use materials, which can be kept at the PM for a certain period of time. The strategy is often applied for screws and other small parts.
2. Demand-driven, material to value-add PM strategy (e.g. shopping basket system): eligible strategy for variant-specific parts that don't justify a storage at a PM.
3. Demand-driven, material storage defined PM (e.g. assembly at material shelf): eligible strategy, if functional segmentation is material-driven only. The strategy leads to PMs of material shelfs with small technical equipment, usually only hand tools and small power tools, often carried by the operator or installed on the material flow PM which then turns into a mobile assembly assistant, with a one-to-one assignment of order to material flow PM.

Next to the classical decision factors, such as consumption, value, or size of parts, the decision on the material supply strategy needs to take existing material supply strategies into account. If different supply strategies are selected for different materials to be supplied to the same PM, it needs to be checked if an according process module configuration is available which integrates both strategies. Often, the selection of material supply strategies forces an iteration from the production system design to the process module design, to add additional branches of input buffer to the hierarchy of a process module. Furthermore, the previously selected material flow PV_i influence the material supply strategy. While e.g. a tugger train is capable to execute consumption-driven strategies very well, it cannot be used for the execution of self-picking material supply. A selection of AGV systems or man-driven transport manipulators are flexible to execute both consumption and demand-driven strategies.

6.2.3.4 Order sequencing process logic

Order sequencing defines the priorities of orders on joint resources. In a matrix production system, this includes the new tasks of order distribution on same-function PM and operation sequence planning (Section 2.1.4.2). The decision on the order sequencing process logic determines, together with the product architecture of produced variants, how the reference process-object model of the system (Section 5.1.4) is manipulated during operation.

Order sequencing, order distribution and operation sequencing direct orders onto PMs and, thus, influence the dimensioning of buffers and the course of heavily frequented transport routes. It is not in the scope of this thesis to develop matrix-tailored new order control strategies. With its influence on the layout design through buffer sizes and transport network, a decision on the optimization criteria and the principal order sequencing logic must, however, be taken. Common optimization criteria are, e.g., FIFO, descending longest operating time, throughput time minimization, utilization of stations or externally driven priorities, such as the urgency of customer orders. It must, furthermore, be decided if the sequence of PMs of an order is defined up-front, before an order enters the production system, or ad-hoc, after each process execution on a PM, with respect to the overall system status or a comparison of the status of next-possible PMs. For reasons of productivity, a PM should execute all possible production operations, before releasing an order for further transport to another PM of the SOO.

6.2.3.5 Material flow process module and buffer dimensioning

The number of material flow process modules and the size of material buffers are mutually dependent of the transport frequency in the system: The higher the frequency of transportation, the smaller the size of the buffers. Transport frequency depends on the material supply strategy and the order sequencing process logic, but also on the transportation time between value-add PMs and the number of transport requirements in the system. To allow for a material flow process module and buffer dimensioning before the design of the actual layout, a mean transport time TT between value-add PMs is specified by the mean distance between two adjacent value-add PMs, divided through the speed of selected material flow process modules (Equation 6.13). The transport requirements depend on the processing time of orders on the different value-add PMs of the system. Orders require variant-individual processing times on different PMs. It is however possible, to calculate the individual mean processing time PT of each PM (Equation 6.14), by division of the volume-weighted PT_i of each assigned operation$_i$ by the overall volume on the PM.

$$TT_{mean} = \frac{Distance_{mean}[m]}{Speed_{PV-Transport,mean}[m/sec]} \tag{6.13}$$

$$PT_{mean} = \frac{\sum_{i=1}^{j} PT_i Volume_i}{\sum_{i=1}^{j} Volume_i}[sec] \tag{6.14}$$

To estimate the number of material flow process modules (PMs), the number of transport requirements for each selected material flow PV$_i$ per defined time period needs to be multiplied by the mean transport time and put into relation to the capacity of one material flow PM in this time period (Equation 6.15). If material flow PM are bound during value-add process execution, the number of value-add PM needs to be added. The same accounts for the number of material flow PM that are bound in input and output buffers of value-add PMs. Dimensioning of material flow instances and buffers is, thus, an iterative process. Depending on the selected material flow PV_i, an additional safety factor SF for service and recharging may apply.

$$Mat.\ flow\ PV\ instances = \frac{Transp.req.\ \cdot TT_{mean}}{Capacity[1/PM]} + \sum Process, Buffer + SF \quad (6.15)$$

Buffers are integrated into the system to bridge a waiting time for the next material delivery. Buffers also compensate process time variations of sequenced PMs in the system. If the harmonization strategy of the system (Section 6.2.3) allows for individual run times of certain value-add PMs, the material flow input buffer of those PMs, furthermore, takes the task of interim storage to the extent of the capacity disharmonization[134].

The ultimate target is a high utilization of value-add PMs, especially if they are operated manually, or if they are built from investment cost-intensive systems. Therefore, the minimum number of input buffers of any value-add PM is one, to enable a queue of subsequent orders in front of each value-add PM. If no immediate transport of an executed order out of the value-add PM can be ensured, the minimum number of one buffer space also applies to the output buffer.

Beyond these minimum buffer capacity, the needed input- and output buffer capacity per value-add PM is estimated by summation of the needed buffer capacities to bridge material delivery waiting time and the average number of produced units $\overline{U}$ per individual run-time reduction of the value-add PM (Equation 6.16)[135].

$$Buffer\text{-}capacity = \frac{CT_{Mat.flow}}{PT_{mean}} + \overline{U} \quad (6.16)$$

The material flow cycle time $CT_{Mat.flow}$, used for dimensioning of buffer capacities, depends on the selected material flow PV_i, which operate either continually (e.g. AGVs) or are scheduled discontinually (e.g. milkrun operation with tugger train).

The calculations of TT_{mean}, PT_{mean}, and average number of units are only approximations, based on mean values and the static assignment of production operations to PMs (Section 6.2.3). Consequently, the dimensioning of buffers and material flow PMs instances reflects a mean value calculation, that only partially satisfies the complexity of

[134] A buffer is never able to compensate equally-operating disharmonized value-add PMs, as the mean capacity difference does not vary, overall, in this case.

[135] The compensation of process times is neglected in this static buffer dimensioning, as the value-add PM relations are too complex for a calculation on average values. Buffer capacities must be validated, considering a dynamic system state during operation, e.g. by material flow simulation

a dynamic operation. The results of the material flow dimensioning are used to finalize an ideal layout. They must be validated, and potentially iterated, in a dynamic material flow analysis. The subsequent evaluation of the production system design embodiments integrates such a dynamic material flow analysis with the help of simulation.

As a result of the buffer dimensioning, the final detailed design of selected value-add PM must follow. A best-point arrangement of materials, tool, and fixtures must be achieved, to ensure a high productivity in manually-operated process modules. If a PM integrates a high number of production operations with many different materials supplied in material-specific bins, a PM may be too large for a potentially limited available space, or cause long walking distances for operators. Corresponding constraints are analyzed in the production system evaluation, eventually causing an iteration back to the process module configuration, or even to PV_i selection, where operations may be split onto different PV_i.

6.2.3.6 Production system ideal layout

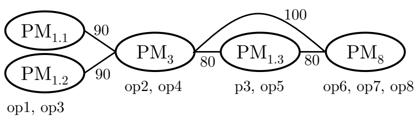
The dimensioning of the material flow elements defines the buffer dimensions and the size of the transport routes of the system for the layout planning. To achieve a transport-efficient layout, the material flow density is analyzed, following the process flow-oriented line-up of PMs. Material flow density is made transparent through an adjacency matrix of transported volumes between PMs (Figure 6.22), reflecting the SCC of the system. An element $a_{ij} > 0$ in the matrix indicates, that the vertices of PM_i and PM_j are adjacent in the graph. The value of a_{ij} quantifies the density of the material flow in pieces per time period. For the overall variant mix, it follows $a_{ij} = \sum_{k=1}^{n} a_{ij,k}$, for k variants. Reflows - according to the static, process flow-oriented assignment of production operations to PMs - are visible in the adjacency matrix by element entries $a_{ij} > 0$ in both triangulars of the matrix.

To derive a layout, heuristic methods from factory planning[136], such as the commonly used modified triangle method of Schmigalla (1970) (Figure 6.23), are suitable.

A layout is most flexible, if all PM are arranged next to two-directional material transport routes for both, the supply of raw materials as well as the material flow of produced goods. This ideal flexible layout needs a project-specific adaption to meet building restrictions and to reach higher area productivity.

[136] Alternatively to heuristic methods, there are a layout design by trial and analytical methods. Trial is purely based on the experience of a designer. Analytical methods require high computational efforts and are not widely used in factory planning. Common heuristic methods are constructional methods, exchange methods, and combination methods. (H-P. Wiendahl 2014, pp. 9.25–9.27)

Max- configuration PM SCC | adjacency matrix



no.pcs.	$PM_{1.1}$	$PM_{1.2}$	PM_3	$PM_{1.3}$	PM_8
$PM_{1.1}$			90		0
$PM_{1.2}$			90		0
PM_3	0	0		80	100
$PM_{1.3}$			0		80
PM_8	0	0	0	0	

Figure 6.22: Adjacency of PMs

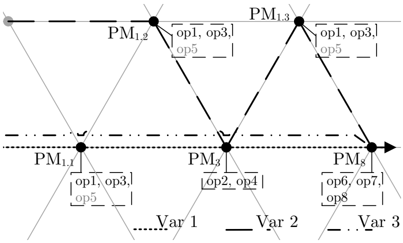


Figure 6.23: PM arrangement

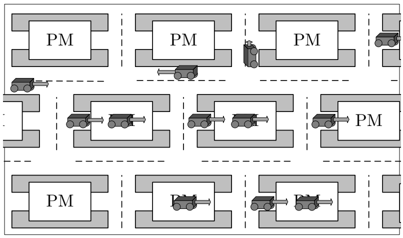


Figure 6.24: Layout of a matrix prod. system

6.2.4 Evaluation of production system design embodiments

The final step of the production system design is the design evaluation. The evaluation reveals how well the input constraints of the system design are met. A comparison is made possible for several alternative design embodiments. If the evaluation does not result in a satisfactory result, an iteration of the system design is necessary. Alternative system designs can be generated by alteration of design choices during the design process.

The reference model serves to maximize changeability and productivity as general input constraints (Section 5.1.1). Actual maximum or minimum limits of productivity parameters, and further, project-specific constraints may be given (Section 6.2.1).

6.2.4.1 Evaluation of system changeability

For the evaluation of system changeability, flexibility and reconfigurability system ranges (fsr, rsr) of the overall system are compared in the dimensions of the change barriers, and related to the product variants relevant for the design project. The evaluation focuses purely on the excess of system ranges, which are regarded as a positive surplus of changeability if productivity constraints are nevertheless achieved. The overlap of fsr and csr with the flexibility and reconfigurability requirements and the surplus on changeability have already been a selection criteria for process module configuration and selection (Sections 6.1.3 and 6.2.2.1).

6.2.4.2 Evaluation of system productivity

Personnel productivity, asset productivity, and area productivity built the reference KPI system, to judge on the system productivity (Figure 5.3). All three KPIs share the system's output, measured in produced quantities per time unit, as a numerator for the calculation of their ratio. Denominators are defined as needed personnel to operate the system, investment cost, and the area requirement of the designed production system. Area and investment cost are fixed values that can be derived directly from the system design result (Table 6.2). Output quantities, on the other hand, depend strongly on the actual production program. Static calculation is hardly possible. Personnel requirements depend on the production program and the harmonization strategy of the system which defines how to handle a under-utilized PM (Section 6.2.3).

To obtain reliable quantities for the calculation of the production program-dependent parameters, it is necessary to valuate the system's dynamic behavior. A discrete material flow simulation helps to determine output quantities of different production program scenarios. The simulation model must map the respective production system design embodiment by its organizational and process structure and, at the same time, serves to review the material flow and buffer dimensioning.

The higher the resulting ratios of personnel, investment, and area productivity, the better. The resulting productivity ratios allow a comparison of different production system design embodiments or a comparison to a status-quo production system.

<table>
<tr><th>KPI parameter</th><th>Influencing factors</th><th>Quantification source</th></tr>
<tr><td>Output [qty/time] (numerator)</td><td rowspan="2">Production program</td><td>Material flow simulation</td></tr>
<tr><td>Personnel [€/time] (denominator)</td><td>Harmonization strategy</td></tr>
<tr><td>Investment [€] (denominator)</td><td rowspan="2">Value-add and material flow PM</td><td>PM instantiation</td></tr>
<tr><td>Area [m^2] (denominator)</td><td>Layout</td></tr>
</table>

Table 6.2: Quantification of productivity KPI parameters

6.3 Conclusion on the design method

The design method pursues a process-driven design of a modular production system. Accordingly, it implements the solution concepts underlying the hypotheses formulated at the beginning of this thesis (Section 1.3). Other than state of the art production system design methods, the segmentation of process functions does not consider capacity requirements or the architecture of specific product variants. The functional scope of each process module is purely defined by the process requirements of similar production operations to be executed on that process module, independent of associated product variants. Furthermoe, the approach of change barriers only considers process limitations when designing the functional scope of a system's process modules. Thus, the method designs process modules which may be utilized by several value streams of different variants. This results in potentially higher-utilized process modules in the production system.

The two-step design approach allows an instantiation of process modules into a production system in the required capacity of a specific planning use case.

From this theoretical considerations, the method should allow to design changeable and highly productive production system for personalized production.

The design method itself contains the two disctinct types of design actions (Section 4.1.3): creative problem solving and analysis, to determine if a proposed solution is rationale. The method defines a structured design process and forces the designer to consider system constraints during the design process, as required (Section 4.2.1). Furthermore, The two axioms of AD ensure a comparison of requirements and selected design solutions, as well as an evaluation of alternatives. The theorems of AD serve as general decision guidelines.

All in all, it is reasonable to assume that a successful production system design for personalized production is possible with the application of the design method. However, this can only actually be proven through a validation project.

7 Validation

To prove the effectiveness of the methodical system for production system design, empiric inductive reasoning may be applied (Section 1.4.1.2). As a validation project for the implementation, a detailed design of a production system for the production of servomotors was carried out. The process-oriented design approach for a modular matrix production system has proven to be useful to fulfill the requirements of personalized production. The hypotheses of this thesis were, thus, confirmed.

The following sections describe the validation project and discuss its suitability for a personalized production system design (Section 7.1), present the application of the methodical design system (Section 7.2) and reflect on the embodiment of the production system design and the design process, relative to the requirements of personalized production (Section 7.3).

Figure 7.1: Examples of servo motors (source: Fertig Motors GmbH)

7.1 Initial situation at the validation partner

The industrial validation partner of this thesis is a German SME that develops and manufactures servomotors and servo actuators and primarily sells them to the packaging machining industry. In the validation project, a production system was designed for the servomotors production of the validation partner. At the time of the validation project, the yearly output of servomotors was around 40.000 units. The enterprise expected a yearly increase of volume of around 30% in the following four years.

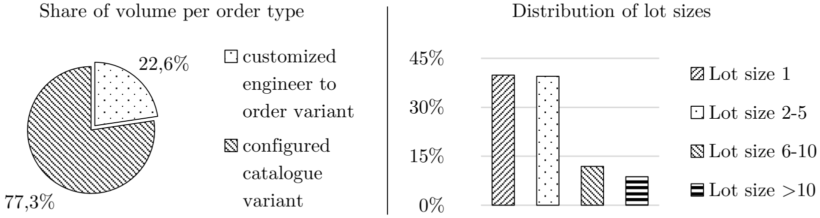


Figure 7.2: Share of lot sizes and order types of the validation project

Servomotors are offered by the enterprise as configured and customized products. The average share of customized products, which are individualized by an engineer-to-order process, accounted for approximately 22% of the yearly volume (Figure 7.2, left).

92% of all orders resulted in production lot sizes of less than ten units. Around 40% of the overall volume was ordered in lot size one. Another 40% of orders had to be produced in lot sizes of two to five units. The majority of orders with a lot size larger than 10 were project orders of customized products (Figure 7.2, right).

The product range comprised seven different servomotor sizes of 40mm-190mm flange square, each available in three different lengths. In the analysis, 86 different manufacturing and assembly operations were identified for the production of configurable variants. Another twelve operations were known to the manufacturer from previous customized orders. There are certain production operations that only apply to certain sizes of servomotor variants. The configuration options, such as number of rotor packs, inertia, brake, or resolver, result in tremendous process time variations in assembly. There are further processes, such as resin socketing, heating and cooling processes, or the assembly of variant-specific parts, that depend on the type or the size of a servomotor variant. There are additional process-dependent dispersions of process times, such as manual testing processes, manual assembly processes, or balancing of the rotors.

Configurable products contain customer-specific parts, such as lid design and parametrization of shaft length and shaft-hub connection. Customized products partially show a highly modified product design, such as a different product architecture, additional electronic and mechanical mounting parts, altered housing shape, or specific packaging.

The validation partner did not expect the product's production operations of future configurations to be tremendously different from the known product spectrum. However, a different family of variants was being developed. The required production operations of this new product family only reduced certain rotor and stator preassembly operations. No totally new production operations were expected for the main assembly.

Targets	**Status quo**	**System design**
Output (2shifts, 240 working days)	40.000 units/year	>100.000 units/year
Capacity flexibility	+/- 30-50%	
Production lot size	batches of order size	one piece flow
Throughput time	reduction compared to status quo	
Personnel productivity	increase compared to status quo	
Constraints		
Variant Flexibility	>95% of product configurations	
Reconfigurability	reconfigurable concept for a later integration of bottleneck stations	
Standardization	design of standardized workstations	
Investment cost	reuse of available machinery to reduce investment cost of realization	
Quality	design system that fosters first time right approach	

Table 7.1: Targets & constraints of the validation project production system design

Prior to the validation project, the existing servomotor production system was segmented into seven process sections, operated as production groups. Each section executed a number of production operations: machining, preassembly, assembly, connection technology, testing, finishing and packaging. Most production operations were executed manually. Some sections included partially automated machinery, such as lathe and milling machines, hydraulic press machines, balancing machines, and partly-automatic testing equipment. Orders were not passed on to the next section until the end of a shift, resulting in high inventories and an average throughput time of seven days.

There was a certain rate of rework which was largely due to incorrect matchings of rotors and stators and forgotten, configuration-specific assembly operations. To harmonize capacities, a flexible working time model was in place, and personnel was shifted between different production groups during the shift by the assembly supervisor. Nearly all needed assembly parts were supplied by an order-specific shopping basket system, picked one shift in advance. Some parts were held available in self-picking material shelves, close to the workstations.

At the start of the validation project, the management expressed targets and constraints for the production system design (Table 7.1). In the validation project, two production system design embodiments were designed. The first design embodiment was a pure application of the developed methodical system, resulting in a matrix production system design embodiment, as envisioned in the objective of this thesis. In the second design embodiment, a balanced assembly line was designed for some main assembly, contacting and testing operations for certain configurations of the servomotor sizes of 55 mm-100 mm flange square[137]. For all remaining assembly operations a matrix production system was designed.

The remaining operations were not integrated in the line to reduce the configuration-related spread of process times to an acceptable degree for the line balancing. Long heating and cooling phases furthermore prevented a possible integration of preassembly operations. Another line for other flange square sizes was not pursued either, as their output was too small to justify the area consumption for a dedicated line. The second embodiment was designed for comparison with the overall matrix production system, as it was the validation's partner original motivation for the project to alter his production system to lean assembly lines.

The following sections introduce the design of the first matrix production system design in detail and compares all design embodiments with the status-quo system of the manufacturer.

7.2 Application of the methodical design system

7.2.1 Process Module Design

Of all identified production operations, there were only four manufacturing operations[138]. All other operations were assembly operations. For each value-add production operation, all material flow operations (of required blank and assembly parts to a process module, as well as transportation of a processed part or subassembly to a subsequent process module) were listed.

The analysis of manufacturing operations showed that one functionally integrated machining process module was conceivable for turning and grinding. A second machining process module was considered to realize marking operations. It was not conceived possible to execute all value-add assembly operations on one assembly process module. The impossibility of one universal assembly process module was evident for the product spectrum of configured variants already, without consideration of customized variants.

Consequently, a change barrier analysis concentrated on assembly. An automation assessment of all identified value-add operations was carried out to span the solution space

[137] The author was supported in the analysis phase of the validation project and in the assembly line balancing and lean line design for the second design embodiment by the project team members Susann Kärcher and Stephan Mayer (Fraunhofer IPA).

[138] At the time of the validation project, the validation partner only machined shafts in-house. All other mechanical and the electrical parts were purchased. As the mechanical production was planned to be realized at another manufacturing site of the validation partner, further future machining operations were not considered in the production system design of the validation project.

	Change barrier	Related product or process property
Value add	automated assembly	design of parts and process
	high-investment equipment	specific production technologies
	load limits	
	load limit of manipulators & material transfer systems	weight of parts
	press capacity	required pressure forces
	load limit balancing machines	weight of shafts
	competencies of operators	specific process requirements
Material flow	form fit of transport fixture	shape of transported goods

Table 7.2: Change barriers of the validation project

of both process technology and production equipment. It was found that only a limited number of operations were functionally suitable for automation with the prevalent design of parts and subassemblies.

7.2.1.1 Change barrier analysis

Four principal change barriers with relevance to the value-add operations of the validation project were identified (Table 7.2). The change barrier *automatability* separates manual and potentially automated operations. Certain operations must be split according to specific production technologies which require *investment-cost-intensive equipment*. Investment-intensive equipment needs a high and joint utilization by several product families and cannot be integrated with operations of different processes, which would cause inevitable idle times for the equipment. Pressing operations need to be analyzed for *essential pressure force* which is the dimensioning factor for the selection of press machines[139]. All operations require a split by weight of processed parts and sub-assemblies, due to the *load limits of manipulators and material transfer systems* within the process modules. The *competencies of operators* was identified as an important change barrier for manually executed assembly operations. Certain operations, such as CNC machining and testing, needed specifically skilled operators to run the machines. Other operations, such as balancing and electrical connection operations, at minimum needed experienced operators. Finally, the required *form fit of transport fixtures* was identified as a change barrier of the material flow operations.

[139]The required z-range of the press operations was neglected as a change barrier. The required ranges were generally small enough that any suitable, market-available, standard press offered sufficient ranges.

7.2.1.2 Process module design goal clarification (CA-FR)

Considering the identified change barriers and prevalent as well as projected future production operations, sixteen different CA_i were derived for process module design (Table 7.3).

At first, manufacturing and assembly operations were separated, and all turning and grinding operations for shaft production were clustered into CA_1. All marking operations were clustered into CA_2. Second, functionally automatable assembly operations, as analyzed in the automation assessment, were clustered into CA_3. After an analysis of all CA_3 operations which were all related to the assembly of magnets to the shaft during rotor assembly it was concluded that a common process module for their execution was possible.

The change barrier of high-investment equipment often correlated with necessary operator skills. The respective operations were clustered into CA_4 to CA_6, each specialized on the technologies of testing, painting and heating. Operator competencies also played a major role for clusters CA_7 to CA_9, for which a strong routine is required to execute the respective operations. CA_7 clusters all operations for the electrical connection of the servomotors. The balancing operations (CA_8, CA_9) were further split into two shaft-weight-defined clusters, according to typical load limits of market-available balancing machines which were available at the validation partner.

Two additional clusters, CA_{10} and CA_{11}, were built according to specifically needed equipment, specialized for resin casting and manual gluing operations. Finally, CA_{12} and CA_{13} cluster all other assembly operations. CA_{12} and CA_{13} include operations, for which only manual and power assembly tools are needed, as well as all pressing operations. In the design workshop, all experts concluded that it was possible to integrate needed presses into standard assembly process modules. The assembly operations of CA_{12} and CA_{13} were, however, split by the weight of parts and subassemblies as well as by the required pressure forces. The appropriate limit of the flexibility design range fdr was set at 10 kg, since this was considered a reasonable weight to be handled occasionally manually, without a lifting aid. This weight limit of parts and subassemblies correlated with a required press force limit of 250 kg.

Three more clusters were derived from the material flow operations. In the discussion on potential solutions, it was considered possible to integrate the transportation of all shafts and rotor subassemblies by use of a shaft- and rotor-universal transportation fixture (CA_{14}). Similarly, a joint transportation process module for stators and engine subassemblies after stator rotor marriage was considered possible (CA_{15}). A third cluster, CA_{16}, was built for the supply of material bins to process modules.

FR_i were mapped to CA_i in a one-to-one mapping, associated with quantification of the design ranges in the change barrier categories. Many of the identified change barriers

change barrier changeabil.	CA_i	operations	FR_i specification	change barrier process capability
- (machining)	CA_1	turning and grinding	$FDP = \{turning, grinding\}$ $FDP = \{machinist\}$	dimens. tolerance; surface finish
	CA_2	marking	$FDP = \{emboss\}$	marking depth tolerance
automated assembly	CA_3	rotormagnet assembly	$FDP = \{glueing\}$	positional tolerance
high investment, or special equipment, skilled operators	CA_4	testing	$FDP = \{testing\}$ $FDP = \{technician\}$	—
	CA_5	painting, incl. drying	$FDP = \{painting\}$ $FDP = \{varnisher\}$	—
	CA_6	oven processes	$FDP = \{heating\}$	temperature variation tolerance
skilled operators & load limits	CA_7	electrical connection	$FDP = \{el.\ routine\}$ $FDP = \{crimping, pin\}$	—
	CA_8	balancing	rotor $fdr = [3kg, 7kg]$ $FDP = \{balancing\}$ $FDP = \{balance\ routine\}$	measure precision
	CA_9	balancing	rotor $fdr = [0, 3kg]$ $FDP = \{balancing\}$ $FDP = \{balance\ routine\}$	measure precision
special equipment	CA_{10}	resin casting	$FDP = \{casting\}$	—
	CA11	manual glueing	$FDP = \{glueing\}$	—
load limits	CA_{12}	other joining (incl. press)	$FDP = \{other\ joining^*\}$ weight $fdr = [10kg, 20kg]$ press $fdr = (25, 300kN]$	—
	CA_{13}	other joining (incl. press)	$FDP = \{other\ joining^*\}$ weight $fdr = [0, 10kg]$ press $fdr = (0, 25kN]$	—
form fit of transport fixture	CA_{14}	rotor transport	$FDP = \{shaft\ fixture\}$	—
	CA_{15}	stator & engine transp.	$FDP = \{engine\ fixture\}$	—
	CA_{16}	material bin transport	$FDP = \{bin\ fixture\}$	—

*other joining = $\{screwing, inserting, circlip\ assembly, sliding, pressing, wirepre- paration, cleaning, lubrication, labeling, adjust\}$

Table 7.3: CA and FR of the validation project

change barrier changeability	**CA$_i$**	**operations**	**FR$_i$ specification**
special equipment	CA$_{12'}$	oven and shrinking	weight $fdr = [10kg, 20kg]$; press $fdr = (25, 300kN)$
& load limits	CA$_{13'}$	oven and shrinking	weight $fdr = (0, 10kg)$; press $fdr = (25, 300kN)$

Table 7.4: Additional CA and FR of the validation project

couldn't be quantified on a continuous scale, but had to be described in terms of given categories, such as different manufacturing technologies, competencies of operators or form fit of the transport fixtures. Quantified flexibility ranges were mainly related to the weight of parts and products. The validation partner expected no future variants to be larger than the current product spectrum but assumed an increase in variants and orders in the lower-sized product spectrum. The flexibility ranges were defined to already cover this future development of the change barrier values. Consequently, no further reconfigurable ranges were defined.

7.2.1.3 Process module hierarchy (FR-DP)

To each *CA-FR* mapping, a process module hierarchy from the functions-object reference model (Section 5.1.1.3) was assigned. The CA$_i$-clustered operations were analyzed with respect to the assigned reference model, to identify couplings in the *FR-DP* mapping and the necessity of an adaptation of the reference model. A coupling was identified between FR$_6$ and FR$_{10}$: It is not possible to perform a transport operation between the oven processes of CA$_6$ and the resin casting operations of CA$_{10}$, as parts and assemblies wouldn't keep their proper temperatures. To handle the coupling, FR$_6$ and FR$_{10}$ were treated as a decoupled design in the subsequent design steps. The design matrix for the *FR-DP* mapping reflects a decoupled design (Equation 7.1).

Another coupling was identified between the temperature-related operations of FR$_6$ and the shrinking operations, which are represented by FR$_{12}$ and FR$_{13}$. As the coupling only accounts for some of the clustered operations, two new clusters, CA$_{12'}$ and CA$_{13'}$, were built (Table 7.4). Those clusters integrate the coupled oven and pressing operations, consequently resulting in a process module hierarchy with two value-add activity branches. The introduction of CA$_{12'}$ and CA$_{13'}$ resolves the coupling between FR$_6$ and FR$_{12}$, and FR$_6$ and FR$_{13}$, as there are only cold joining operations left in CA$_{12}$ and CA$_{13}$.

CA$_{12}$ and CA$_{13}$ remain with all cold pressing and all other assembly operations. To enable the execution of different pressing and assembly operations, there are several manual tools, power tools, and an appropriately dimensioned press with variant-specific press stamps necessary. For the *FR-DP* model of the process module hierarchy, this means multiple force transfer (DP_{21m45}) and joining (DP_{21m46}) activities, whereas some hand-held tool and gripping activities are carried out directly by the human manipulator. Consequently, force transfer activities as well as gripping activities for material transfer were deleted from their decomposition hierarchy. However, DP_{12} and DP_{13} had to integrate two activities for base part buffering, since both the stator and the rotor are to be seen as a base part for certain operations, before they are finally joined. Furthermore, most assembly clusters didn't need the eject residue branch of the decomposition.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_7 \\ FR_8 \\ FR_9 \\ FR_{10} \\ FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{12'} \\ FR_{13'} \\ FR_{14} \\ FR_{15} \\ FR_{16} \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathbf{x} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathbf{x} & 0 & 0 & 0 & \mathbf{x} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \\ DP_8 \\ DP_9 \\ DP_{10} \\ DP_{11} \\ DP_{12} \\ DP_{13} \\ DP_{12'} \\ DP_{13'} \\ DP_{14} \\ DP_{15} \\ DP_{16} \end{Bmatrix} \tag{7.1}$$

7.2.1.4 Process module configuration (DP-PV)

To add to the knowledge base of functions, all machinery, production equipment, tools, and workstations that were in place at the validation partner's production system at the time of the validation project were qualified according to their flexibility system ranges relative to the change barriers. Furthermore, automation concepts and new oven concepts from system integrators, previously requested by the validation partner, were included as respective solution elements in the knowledge base of functions. For the validation project, the validation partner enquired state-of-the-art workstations, material supply systems for workstations, stripping and crimping machines, and manually-operated electrohydraulic

	Name	ID	investment-technology [string]	operator competency [string]	rotor weight min [kg]	rotor weight max [kg]	weight of parts min [kg	weight of parts max [kg]	pressure force min [kg]	pressure force max [kg]	form fit of transport fixture [string]	Reconfigurability (yes/no
2	3to lever press	8001	pressing	NV	NV	NV	NV	NV	0	3000	NV	no
3	Lever press Schmidt-VI	8002	pressing	NV	NV	NV	NV	NV	0	250	NV	yes
4	Servo press Schmidt-X	8003	pressing	NV	NV	NV	NV	NV	0	500	NV	no
5	Pneumatic vertical scre	8004	screwing	NV	NV	NV	NV	NV	NV	NV	NV	yes
6	Powertool drill driver	8005	screwing	NV	NV	NV	NV	NV	NV	NV	NV	yes
7	Balancer 1	8006	balancing	balance routine	0	3	NV	NV	NV	NV	NV	no
8	Balancer 2	8007	balancing	balance routine	3	7	NV	NV	NV	NV	NV	no
9	CNC-Center	8008	turning; grinding	machinist	NV	NV	NV	NV	NV	NV	NV	no
10	Dot peen marker	8009	embossing	NV	NV	NV	NV	NV	NV	NV	NV	no
11	Oven Chamber	8010	heating	NV	NV	NV	NV	NV	NV	NV	NV	no

F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 | F10 | F11 | F12 | F1 ...

Figure 7.3: Knowledge base of functions of the validation project (excerpt)

and mechanical bench power presses. The knowledge base was implemented as an excel spreadsheet per function, for ease of use and future expansion of the validation partner's production system designer (Figure 7.3).

For the system design of the validation project, functionally pre-instanced process modules were configured from the knowledge base of functions. A standard workstation system was selected for all assembly stations, only differentiated by required manually operated assembly tools and machines. Since this was the first overall system design of the validation partner, only one process module pre-instance was configured for most CA_i, essentially predefining the later selection of process modules during the system design. For many of the configured process modules, the existing machinery and equipment of the manufacturer were incorporated, to reduce overall needed investment.

The configuration included a comparison of system ranges with design ranges and the calculation of the information content I. All process module pre-instances were at first configured to fulfill all known changeability requirements of the clustered operations, i.e. $I_{changeability} = 0$. Process-capability-related change barriers were not evaluated. It was concluded that there is available equipment and machinery on the market, to cover the process capability requirements of all operations of each CA_i. Nevertheless, for the selection of actual production equipment, required process capabilities had to be considered.

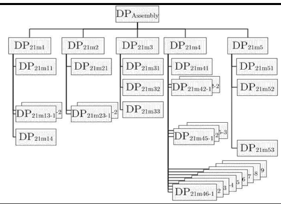
The process module hierarchies mapped to CA_{12} and CA_{13} provided for the configuration of a universal manually-operated assembly cell, equipped with all relevant tools and processes. The subsequent production system design forced an iteration back to the process module configuration, eliminating screwing and pressing tools and equipment from some of the PV_{12} instances. The result was a new process module configuration $PV_{12''}$, able to perform manually operated assembly processes (except screwing and pressing), and equipped with a handling device to manipulate parts up to 20 kg. The need for

Process Module

Name	Heavy assembly module
processes	main assembly operations
Technology	insert, press, screw, slide, assemble circlip, adjust
Automation	manual station
ID	PV12

Invest	€47.900,-
Area	4,5qm

Hierarchy



Comments

All main assembly operations, size 140, 190.

			investment-technology [string]	operator competency [string]	rotor weight min [kg]	rotor weight max [kg]	weight of parts min [kg]	weight of parts max [kN]	pressure force min [kN]	pressure force max [kg]	form fit of transport fixture [string]	Reconfigurability (yes/no)	surface finish	positional tolerance	marking depth tolerance	temperature variation	measure precision
Configuration	**FSP, fsr, sr__is**		insert; press; screw;slslide; circlip; adjust	other	0	10	0	50	0	30	NV	yes	NV	NV	NV	NV	NV
	RSP, rsr, sr__future		other	Ω	0	10	0	50	0	30	NV	-	NV	NV	NV	NV	NV
Other process capabilities (not change barrier relevant)																	
Flexibility																	
F1	**Configured Function: Guide handling (Manipulators)**																
F2	**Configured Function: Define pick position (Centering fixtures)**																
F3	**Configured Function: Connect material (Part Buffer)**																
F4	**Configured Function: Contact, Transfer, Place (Material Transfer System)**																
DP21m14	JumboFlex Handling Device	ID4001	NV	NV	0	50	0	50	NV	NV	NV	no	NV	NV	NV	NV	NV
DP21m53	JumboFlex Handling	ID4001	NV	NV	0	50	0	50	NV	NV	NV	no	NV	NV	NV	NV	NV
F5	**Configured Function: Guide value add (Process Manipulator)**																
DP21m31	normal operator	ID1001	NV	other	0	10	0	10	NV	NV	NV	yes	NV	NV	NV	NV	NV
DP22m41	normal operator	ID1001	NV	other	0	10	0	10	NV	NV	NV	yes	NV	NV	NV	NV	NV
F6	**Configured Function: Tranfer Manufacturing Force (Manufacturing Machine)**																
F7	**Configured Function: Re-Shape/Change Material (Manufacturing Tool)**																
F8	**Configured Function: Transfer Joining Force (Assembly Device/Machine)**																
DP21m45-1	3to lever press	ID8001	press	NV	NV	NV	NV	NV	0	30	NV	no	NV	NV	NV	NV	NV
DP21m45-2	Power Tool drill driv	ID8005	screw	NV	NV	NV	NV	NV	NV	NV	NV	yes	NV	NV	NV	NV	NV
DP21m45-3	Pneumatic vertical s	ID8004	screw	NV	NV	NV	NV	NV	NV	NV	NV	yes	NV	NV	NV	NV	NV
F9	**Configured Function: Join Parts (Assembly Tool)**																
F10	**Configured Function: Define part position (Jig)**																
F11	**Configured Function: Define auxiliary position (Auxiliary holder)**																
F12	**Configured Function: Move Goods (Transport Manipulator)**																
F13	**Configured Function**																
Reconfigurability																	

Figure 7.4: Knowledge base of process modules of the validation project (excerpt)

$PV_{12''}$ was identified during the capacity harmonization and process-oriented line-up of the PMs, which disclosed that some PV_{12} process module instances were fully utilized by the preassembly of stators as well as in the packaging area. None of the two areas contain screwing and cold press operations.

Similar to the knowledge base of functions, all functionally pre-instanced process modules were saved in an excel spreadsheet, as a knowledge base of process modules. Each pre-instance was qualified by its flexibility and reconfigurability system ranges relative to the change barriers. Other process capabilities, relevant to the production operations, were also qualified in the knowledge base of process modules (Figure 7.4).

7.2.2 Production system design

The matrix production system design of the validation project started with the modeling of the max-configuration precedence graph which related the production operations of the current production program. The production operations reflected all configurations and additional customization operations which were already used for the process module design. A basic variant processing time of all production operations was recorded in a time study, and configuration additions were added for configuration factors, such as, e.g., additional rotor packs, inertia, and brake. Process module instantiation, process module relation, and the design of a layout followed.

7.2.2.1 Process module instantiation

For the selection of value-add PV_i for each value-add operation, a selection table was built. This was the first systematic production system design at the validation partner, so generally, only one fitting PV_i was designed for the previously defined CA_i, with two exceptions:

The functionally pre-instanced manual glueing process module PV_{11} which was built for CA_{11} operations is capable to execute CA_3-operations (automated assembly of rotor magnets) as well. Conversely, PV_3 cannot execute all operations of CA_{11}. Corollary 3 suggests integrating multiple operations into one PV_i. Furthermore, an unambiguous assignment of operations to PV_i is promoted by the design method. However, as PV_3 was the first automated assembly cell to be integrated at the validation partner, it was decided to only instantiate one automated assembly cell of PV_3 into the initial system setup, to allow for a slow ramp-up phase. Consequently, parts of the volumes of the CA_3 operations would have to be executed on a PV_{11} instantiation, in order to allow for learning and further ramp up of automated cells.

PV_1	PV_2	PV_3	PV_4	PV_5	PV_6	PV_7	PV_8
35%	55,2%	85%	210%	128,7%	10%	234,9%	37,5%
PM_{11}	PM_{21}	PM_{31}	PM_{41} PM_{42}	PM_{51} PM_{52}	PM_{61}	PM_{71} PM_{72} PM73	PM_{81}
PV_9	PV_{10}	PV_{11}	PV_{12}	$PV_{12'}$	$PV_{12''}$	PV_{13}	$PV_{13'}$
93,6%	167,9%	173%	97,1%	90,8%	261,8%	143,9%	62%
PM_{91}	PM_{101} PM_{102}	PM_{111} PM_{112}	PM_{121} PM_{122}	$PM_{12'1}$	$PM_{21''1}$ $PM_{12''2}$ $PM_{12''3}$	PM_{131} PM_{132}	$PM_{13'1}$

Table 7.5: Capacity harmonization of the validation project

The second exception concerned the oven and resin casting operations. The industrial validation partner had requested alternative integrated station designs from system integrators for CA_6 and CA_{10} operations. However, the decision was taken to keep the current oven and resin casting station in the knowledge base, because the offer of the system integrators would require higher investment and was not intended to be integrated in the first setup of the system.

Since all PV_i had been specifically designed for the validation project, all selected PV_i were capable of executing their operations, not only in relation to the change barriers but also regarding required process capabilities.

The number of required instances per selected value-add PV_i was calculated with the output scenario and the given capacity constraints[140] of the system design (Section 7.1). PM were instanced for every PV_i in a required number to cover the capacity needs for each function (Table 7.5). The utilization of tester PM_{41} and PM_{42} is slightly above 100%. Since the testers are investment-intensive systems, it was decided to not add a third tester, but to keep some area reserved for a later integration of a third system.

From a purely capacity need perspective, one PV_{12} instance (i.e. PM_{121}) was appropriate. However, the decision was taken to integrate an additional PM_{122} into the production system design. The second instantiation gave the opportunity to pair each PV_{13} instance with a PV_{12} instance, ultimately resulting in a universal main assembly process module for all product sizes. The additional PM_{122} builds a flexibility capacity reserve, as a scale-up of volume may be met with an additional operator, replacing a multi-PM operation of PV_{12}-PV_{13}-assembly modules by one operator.

[140]The capacity utilization considers the actually available working time, without consideration of OEE.

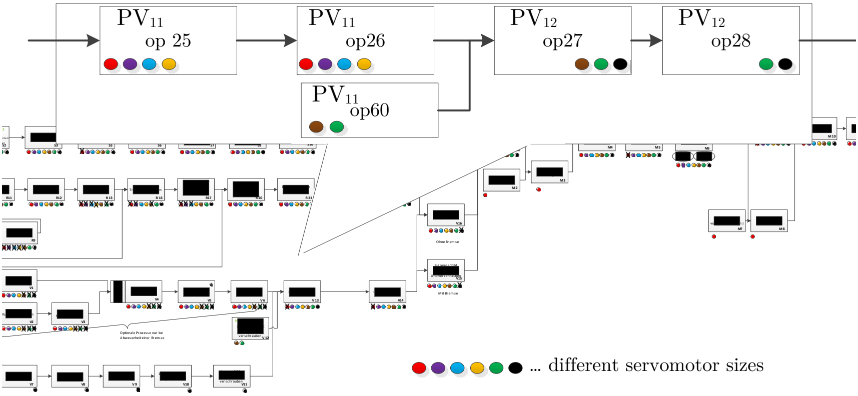


Figure 7.5: Validation case max-configuration graph (excerpt)

7.2.2.2 Process module relation

To analyze the process flow-oriented line-up of PMs, all production operations were displayed in a max-configuration graph of the validation project (Figure 7.5). In the graph, the assignment of operations to PMs was marked. The process flow-oriented line-up showed that most multiple instances of one PV_i are needed at the same spot of the SOO. Only the three instances of $PV_{12''}$ ($PM_{12''1}$, $PM_{12''2}$, $PM_{12''3}$) were distributed between stator preassembly, main assembly, and the packing operations (Figures 7.6 and 7.7). Accordingly, the spread of production volumes between multiple PM instances of the same functionally pre-instanced PV_i is equal for all, but $PV_{12''}$ process modules. The *PV-PM* design matrix indicates the share of production volume spread[141] (Figure 7.8).

Under consideration of the process flow-oriented line-up, a combination of multi-PM operation and individual run times was selected as a harmonization strategy of the validation project. Multi-PM operation was used to achieve the target of a high utilization, as well as an even distribution of operator capacities. The line-up of process modules plays a major role when selecting PM for multi-PM operation, as operators are required to oversee all stations and to walk back and forth among them. The design of the validation project foresees three different strategies to implement multi-PM operations, listed in the following.

[141] This is only a static spread of production volumes, relevant for the layout design. During dynamic system operation, the spread of volumes may differ, depending on an ad-hoc order distribution, as directed by the order control strategy (Section 6.2.3.1). The utilization of PV_{11}, and PM_{111} and PM_{112}, respectively, contains the capacity requirements of CA_3 operations, according to the previously explained split between automatic and manually executed volumes.

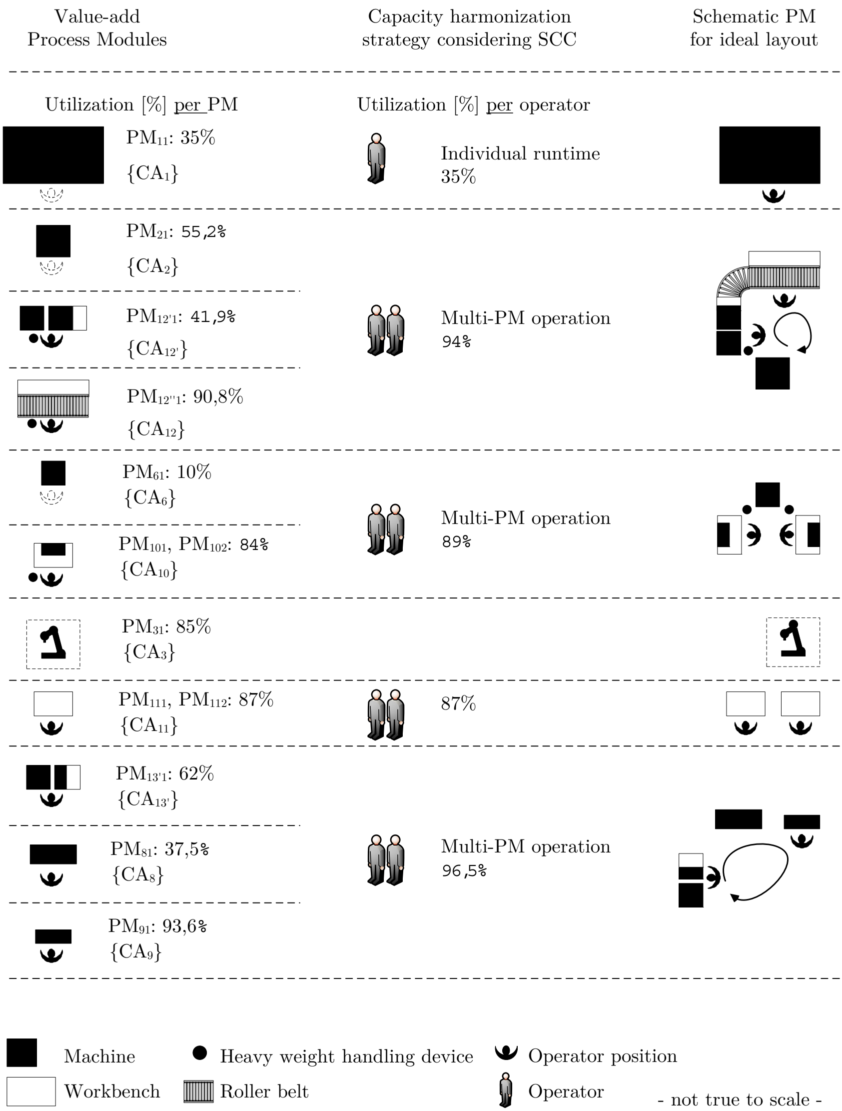


Figure 7.6: PM instances of the validation project in process flow-oriented order (figure 1/2)

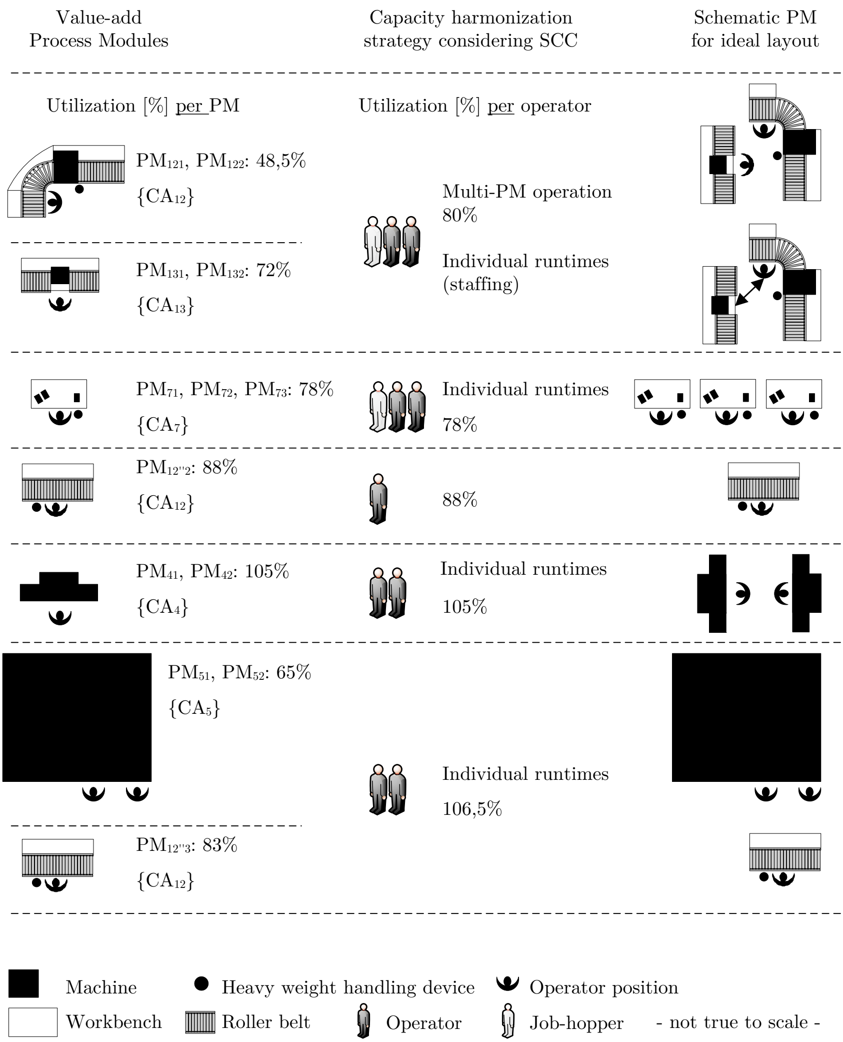


Figure 7.7: PM instances of the validation project in process flow-oriented order (figure 2/2)

$$
\begin{Bmatrix} PV_1 \\ PV_2 \\ PV_3 \\ PV_4 \\ PV_5 \\ PV_6 \\ PV_7 \\ PV_8 \\ PV_9 \\ PV_{10} \\ PV_{11} \\ PV_{12} \\ PV_{12'} \\ PV_{12''} \\ PV_{13} \\ PV_{13'} \end{Bmatrix}
=
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}32 & 0{,}35 & 0{,}34 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{Bmatrix} PM_{11} \\ PM_{21} \\ PM_{31} \\ PM_{41} \\ PM_{42} \\ PM_{51} \\ PM_{52} \\ PM_{61} \\ PM_{71} \\ PM_{72} \\ PM_{73} \\ PM_{81} \\ PM_{91} \\ PM_{101} \\ PM_{102} \\ PM_{111} \\ PM_{112} \\ PM_{121} \\ PM_{122} \\ PM_{12'1} \\ PM_{12''1} \\ PM_{12''2} \\ PM_{12''3} \\ PM_{131} \\ PM_{132} \\ PM_{13'1} \end{Bmatrix}
$$

Figure 7.8: Process module instances of the validation project

1. Single operator, multiple PMs *(Main assembly PM_{121} & PM_{131}, PM_{122} & PM_{132})*: One operator is responsible for more than one functionally independent PM. The operator self-directs capacity to the PM, depending on the length of the order-queue in the input buffer of the different PMs.
2. Multiple operators, multiple PMs *(Stator preassembly PM_{21} & $PM_{12'1}$ & $PM_{12''1}$; rotor preassembly $PM_{13'1}$ & PM_{81} & PM_{91})*: Several operators are responsible for several, often sequential, PMs. Operators are self-organized, according to the principles of a production group, or else the operators conduct the production line balancing approach of a lean-production rabbit chase.
3. Multiple operators, one shared PM *(Oven and resin casting PM_{61} & PM_{101} & PM_{102})*: Several operators are assigned to a specific PM, but additionally share a common supplying PM. Operators have to self-organize the operation of the shared resource.

Individual run times are applied, whenever there are multiple, under- or over-utilized PM instances of one functionally pre-instanced PV_i. The multiplicity of same-function PMs allows for an adjustment of this function's capacity by operating some of the PM instances part-time. In the validation project, this applied for the PM instances of PV_1, PV_{12}, PV_{13}, and PV_7.

The machining shop was planned to only operate one shift per day, producing all orders planned for a next-day assembly. A job-hopper position was defined for the other individual-runtime PMs PM_{121}, PM_{131}, PM_{73}. The role was assigned to the assembly supervisor of the validation partner.

Individual but extended run times apply for PV_4, and for PV_5 and its associated $PM_{12''3}$, since their utilization was above 100%. The extended run times of the six related PMs had to be considered in the required dimensioning of a common inbound buffer[142].

The production system design of the validation project did not foresee a specific order sequence logic. Due to the high variant universality of designed process modules, the system design of the validation project showed a high variant mix flexibility. Therefore, the input variant mix and the order sequence were kept random, in line with actual customer orders. Within a PM, orders were decided to be processed according to a FIFO logic. The eldest order in the waiting queue of a PM was given priority for processing. This was ensured by an appropriate design of input buffers for all PM. Within the overall system, it was considered permissible for orders to overtake other orders. At the transfer from one PM to the next PM, the subsequent PM with the shortest order queue in the input buffer was selected. This resulted in a WIP inventory-controlled order distribution between different PM instances of identical PV_i.

7.2.2.3 Material flow instantiation

At the time of the validation project, the validation partner did not want to invest into the implementation of an AGVs fleet. Instead, a manually operated tugger train system was selected as transport manipulator. Existing assembly trolleys, already supplied with form-fit transport fixtures for the material flow clusters CA_{14}, CA_{15}, and CA_{16}, were selected to be reused. To fulfill the one-piece flow concept, it was decided that all trolleys in an outbound buffer of a PM are to be picked up at every tugger train cycle, regardless of their filling level.

Kanban was selected as the material supply strategy for a large share of the raw materials. Other material numbers were either customer order-specific or had a very high variance of configuration. Order-specific picking and a shopping basket supply strategy was selected for those materials. To create a best-point arrangement of materials in a picking bin and to avoid damage of sensitive parts (e.g. encoder), separate circles of shopping basket systems were designed for rotor preassembly, stator preassembly, and main assembly.

To determine the size of the buffers and the number of material flow PV_i, $distance_{mean}$ and $speed_{PV}$ were estimated and TT_{mean} and PT_{mean} were calculated. In an iterative

142 Only one paint shop system was planned for the production system of the validation project. It was, however, equipped with two paint cells, to be able to operate it with two varnishers.

approach of dimensioning the number of tugger trains, inbound raw material, material flow buffers, and number of operators, it was estimated that one tugger train was sufficient. A second material flow operator was added to cover the picking operations in the warehouse. All inbound raw material buffers were dimensioned to cover at least the duration of one full tugger train cycle in consideration of PT_{mean}. In addition, the maximum size of the material flow buffers was validated by the material flow simulation for the design evaluation (Section 7.2.3). Special focus was placed on the inbound buffer in front of the testing PM_{41} and PM_{42}, since the buffer was needed to cover the additional run times of testers and paint shop. Therefore, the respective buffer was not limited in the simulation, and the simulation runs were analyzed for the maximum amount of units in the buffer. It was found that a maximum of 20 units was an eligible in- and outbound value for material flow buffers in the main assembly area, and the inbound buffer in front of the testing area was analyzed to be 58 units. The selected assembly trolley and transport fixtures are, in general, able to hold 20 pieces. The buffers of assembly PMs were dimensioned to hold two trolleys each.

A decoupling buffer between the pre-assembly areas and the main assembly was, furthermore, added to the system, to ensure that to-be-paired rotors and stators are both available before the start of the main assembly. The order-specific pairing of rotors and stator was assigned to the tugger train operator, supported by a pick-by-light system.

The input buffer infrastructure of the different material supply strategies was already considered during process module design for the validation case. At the time of the validation project, only about 65% of the validation partner's shop floor were occupied. Therefore, a final process module design with a best-point arrangement of all raw materials and tools was not limited by space restrictions. An iteration back to the process module configuration was not necessary.

7.2.2.4 Ideal layout

The material flow analysis reflected separate rotor and stator preassembly sections and a relatively uniform material flow through adjacent PMs (Figure 7.9). An ideal layout was created, using the modified triangle method. The ideal layout was adapted to the building restrictions of the validation partner. Specifically, the current location of the paint shop and the raw material warehouse with its adjacent loading bays put limitations on a one-to-one implementation of the ideal layout. The result was a layout with a main material flow from the warehouse to the wrapping area, with the warehouse and the preassembly areas on one side of the production hall, and the main assembly, testing, painting and wrapping areas located in the second side of the production hall (Figure 7.10).

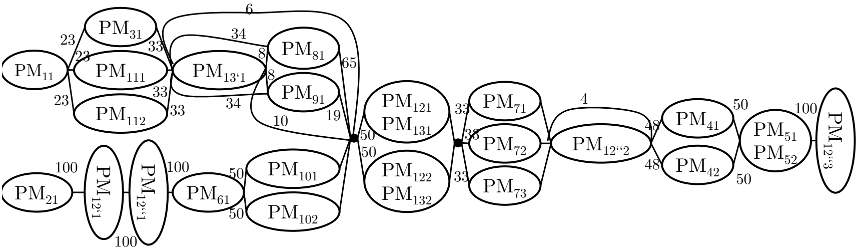


Figure 7.9: Adjacency of PMs

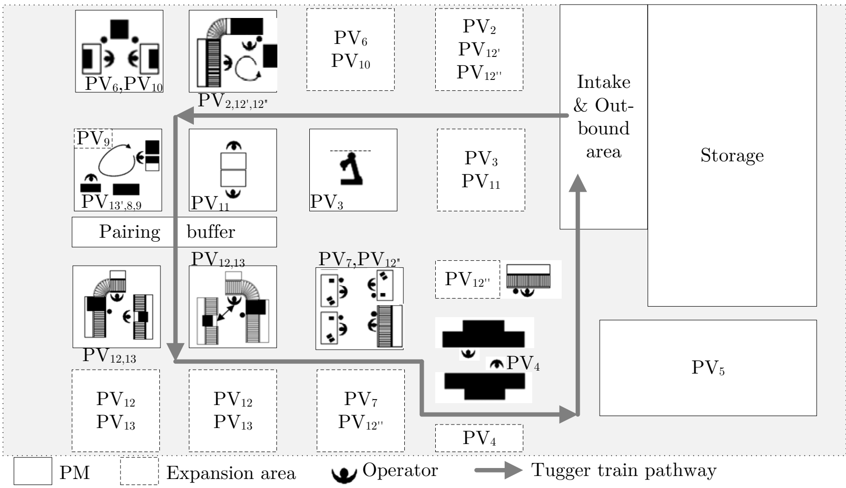


Figure 7.10: Validation case production system layout

7.2.3 Design embodiment evaluation

The design embodiment evaluation of the validation project compared the results of both design embodiments to the status-quo production system of the validation partners qualitatively, by the KPIs of productivity evaluation, as given by the reference model (Figure 5.3). The fulfillment of changeability requirements was discussed with consideration of the target to achieve a flexibility of the production system >95% of product configurations. Furthermore, a qualitative analysis of the overall matrix production system design embodiment showed the fulfillment of the validation project's further constraints and targets, as provided by the management of the validation partner (Section 7.1).

KPI	Status quo	Assembly line & partial matrix	Matrix design
Personnel productivity [shift qty./€]	0,022	0,031	0,042
Asset productivity [yearly qty./€]	—	0,63	1,51
Area productivity [shift qty./m^2]	0,14	0,17	0,25

Table 7.6: Productivity KPI comparison of validation design embodiments and status quo

The matrix design embodiment of the validation project achieved better KPI values of personnel[143] and area productivity[144] than the validation partner's status-quo production system setup and the second design embodiment that integrated an assembly line for motors of 55 mm-100 mm flange square size. It furthermore achieved the best asset productivity of the two design embodiments[145] (Table 7.6).

The denominators (number of operators, investment, production area usage) for the calculating of productivity KPIs were derived from the layout and the result documentation. The dynamic parameter of output quantity was determined with the help of discrete material flow simulation models, mapping the current status quo of the validation partner's production system, and the two design embodiments of the validation project[146].

The simulation models delivered the average maximum output quantities, which were related to personnel costs, the needed investment to implement the system, and the consumed overall area (productive, storage, and transport areas) of the respective production

[143] The calculation of personnel productivity considered all operators in the pre-assembly, assembly, testing, paintshop and packaging areas, the job hopper position (overall matrix design only), as well as the two operators needed in each shift for picking and logistics. The overall number of operators needed per shift in the simulation of the designed systems was reduced by two operators compared to the status quo.

[144] The design of the validation project matrix production system reduced the required area by around 90 m^2. The reduction was mainly due to the reduction of large amounts of raw materials and WIP in the productive areas which the status quo system needed in order to decouple its seven process sections. The design embodiment of partial matrix and assembly line consumed approximately the same layout as the prevalent system.

[145] Asset productivity was not evaluated for the status-quo system, because only the additional equipment investment into a transformation of production systems was evaluated. Transformation cost, such as machine relocation expenses, were not considered in the asset productivity. To implement the matrix production system as designed, additional crimping machines, presses, and industrial-standard assembly stations with flow racks for material supply needed to be purchased. Furthermore, an investment for a tugger train, as well as for other logistical equipment (including a pick-by-light-controlled sorting buffer between the preassembly and the main assembly areas) was needed. Additional work stations were needed for the assembly line. In line with the system constraint of reduced investment cost, a sensible reuse of available machinery and equipment was pursued.

[146] The simulation models were implemented in Java by Lisa Charlotte Günther (Fraunhofer IPA), according to the author's analysis of the status quo of workstations, production system functions, systematics of production control, and according to the documentation of the design embodiments. The simulation model of the status-quo production system ignored waste in the production process, thus enabling a fair comparison between the two systems.

systems. The simulation was run with an actual past monthly production program of the validation partner which was qualified as representative in the given order sequence of customer orders. For the simulation, an infinite supply of orders was assumed, which resulted in 248 hours of simulated production run time. The throughput quantity result of the simulation was split into time slices of seven hours, representing one shift, and then evaluated. The average maximum output quantity was calculated by averaging the output of the 35 fully simulated shifts. Downtimes of individual process models and individual performance levels of operators were not considered in the simulation model. Missing parts, quality break downs, and process-related processing time variations were also not incorporated into the simulation. Variant-related spreads of processing time were, of course, simulated. The simulation used the same data that were collected for the production system design.

In the simulation, the matrix production system design embodiment was the only system that achieved the target of a possible yearly system output of more than 100.000 units in a 2-shift working time model. It achieved an average yearly output of more than 120.000 units in the simulation. By comparison, the status-quo production system's output could be increased to an average of around 75.000 units/year. The second design embodiment integrated one tester system into the assembly line of the design. As it was the bottleneck of the line, the simulation removed about 30% of assemblies from the line before testing and transported these orders to the out-of-line testing equipment. The assembly line lost output due to waiting times of operators, caused by cycle time variations of different configurations[147]. The output of the complete system of assembly line and partial matrix achieved around 93.000 units/year.

Capacity flexibility was tested in the simulation of the matrix production system by a reduction of operators in multi-PM-operated systems and an adaptation of individual run times. A decrease of the output up to 50% was possible through a reduction of operators in multi-PM-operated pre-assembly systems. In the main assembly area, a reduction of output was possible of up to 30% by the same means, but with a loss of operator utilization of approximately 15% at $PM_{12''2}$. The job hopper position which would be required for the operation of this PM in such an output scenario was not tested in the simulation. A further decrease of output in the main assembly area, as well as a general increase of output, is only achievable with a change of working hours up to the elimination or implementation of shifts.

[147] There was no line-specific sequencing of orders (pearl chain) to reduce waiting time losses, but orders were assigned to the line according to the sequence of actual customer orders of the reference production program. An optimization of output in the assembly line could potentially be achieved by according sequencing.

Targets & constraints		
Output >100.000units/year	●	- see simulation results
Capa flexibility +/-30%	●	- individual run times - flexible working-time model
One piece flow	●	- given by design
Reduction of throughput time	●	- elimination of process sections - reduction of status-quo WIP
Increased personnel productivity	●	- see productivity KPIs
Flexibility >95% of configurations	●	- 100% configurations considered - reserve in change barrier categories
Reconfigurable system	●	- modular layout - expansion area for step-by-step investment - scalable staffing
Reuse available machinery	●	- given by process module design
Reduction of rework rate	◑	- pick-by-light pairing - best-point arrangement (materials, tools) - in-process mistakes not further considered

Table 7.7: Evaluation of system constraints achievement

The simulation model further delivered the throughput times of the production systems. The matrix production system design embodiments reduced the throughput time by 80% after the preassembly areas, in comparison to the status-quo production system. The throughput time of an order through the assembly line and partial matrix system was in an average about 1,5 hours shorter than the throughput time in the overall matrix, as the buffer and transport times between main assembly, contacting and testing were omitted. As the matrix system achieved better results in all other evaluation criteria, this slightly shorter throughput time was not seen as a decisive factor in the comparison of the two design embodiments.

The matrix design embodiment of the validation project was also able to fulfill all given targets and constraints (Table 7.7). In the direct comparison with the assembly line and partial matrix, it proved more flexible and reconfigurable and there were less productivity losses. The validation partner decided for the overall matrix production system design for further implementation.

7.3 Reflection on the methodical design system

The methodical design system has proven successful for the design of the production system of the validation project. The validation production-system design embodiment satisfied system constraints and targets, given by the management of the validation partner

Achievements	**Related to**
Successful realization of detailed production system design - improved KPI to status quo - achieved project targets and complied with constraints - possible system operation and SOO	Section 1.4.1.2
Successful implementation of conceptual design - reference model as design target vision - model accepted and considered useful by system designers	Section 1.4.1.2
Challenges of personalized production tackled by design - product spectrum, order types, general business environment of validation use case - 2-stage process module and system design (stepwise investement & reconfiguration)	Section 1.1
Requirements of design method fulfilled - guided, structured design process - supports designers in creative and analytical decision-making - heuristic method (expert knowledge, simplicity of tools & methods)	Section 4.2.1
Criticism	
High manual efforts - two-stage process module and system design - iterative dependency between detailed PM design & material arrangement	

Table 7.8: Reflection on the methodical design system

(Table 7.6 and Table 7.7). The detailed design contains all functional process capabilities to flexibly produce all known configurations of the validation partner, while achieving a higher personnel and area productivity, compared to its status quo production system. The modular layout and the use of a standardized station design for assembly process modules wherever possible permits a later adaptation of system functions, to integrate future variants and technologies. According to the material flow simulation of the design embodiment evaluation, the system's capacity configuration is sufficient for production of the required output in the specified shift model. Within limitations, volume scalability was also possible. The simulation also showed that the variant mix capability of the system design could handle representative production programs of the validation partner. Thus, the production system operation seems possible, fulfilling the sequence operations functionally and satisfying the general production system requirements. It can, therefore, be assumed that the detailed designed production system of the validation project is controllable. Its realizability is, per definition of J. Müller (1990, p. 9, 11) (Section 1.4.1.2), accordingly given.

The validation project proved the fulfillment of the requirements on the design method (Section 4.2.1, Table 4.2). The method was capable to guide the production system design with its structured design process and support production designers in their creative and analytical decision-making. In the validation project, the production system was designed in on-site workshops, in a joint effort with the design team of the validation partner. The heuristic nature of the method made the integration of the design team's knowledge possible. Needed data and information, e.g. processes, PT, SOO, were only collected and analyzed during the validation project. System functions were decomposed to find design solutions for all required processes. In consideration of relevant requirements and constraints, the functional elements of the production system as well as configured process modules were selected for process module and system design by the author and the design team of the validation partner. The design method delivered decision strategies to judge the changeability and process capability of different design solutions. AD's Axiom 2 and the introduced calculation rules and functional ranges helped as a decision model to evaluate alternative design solutions. The reference model of the methodical design system was used as an explanatory model for the system design target vision of the matrix production system.

The product spectrum and the general production circumstances of the validation partner coincide with the challenges of personalized production. Unique customer-required configurations of products with personalized components are produced in very small lot sizes, down to lot size one. Project business and a turbulent business ecosystem make the prediction of production volumes and specifically a prediction of the variant mix nearly impossible and require a high degree of capacity flexibility. The validation partner expected an increase in volume, but estimated a risk of over-forecasting. Since the challenges of the validation project correspond to the challenges of personalized production and a successful application was possible, the developed methodical design system solves the identified deficit of a lacking method for the process-oriented design of matrix production systems (Section 1.2). The validation also supports the hypotheses, formulated in the problem statement, by inductive reasoning. The methodical design system explicitly addresses functional process capabilities and builds a modular production system layout.

Advantages and disadvantages of the methodical design system were discussed with the system design team after the validation project. Critized were the efforts needed for the design method, especially with regard to the two stages of process module design and process module selection. On the other hand, the knowledge bases of functions and process modules were appreciated as valuable collections of solution elements for later production system design projects.

A potential point of criticism is related to the iterative dependency between a detailed process module design and the number of raw materials and tools to be supplied to the operator at a PM in a best-point arrangement. The focus on change barriers for the functional segmentation of the system resulted in large assembly process modules of numerous operations for numerous variants. Due to the selected Kanban material supply strategy of the validation project, a significant number of material bins had to be included in the assembly PMs. In the case of the validation project, available space was not a limitation. However, the availability of area is often a major problem in production system design projects. In the case of limited availability of space or emerging long walking distances for operators to manipulate the respective PM, a detailed process module design according to lean-line design principles may be pursued. Alternatively, a further segmentation of production operations, according to state-of-the-art methods for a product- or capacity-oriented segmentation of assembly operations in a modular assembly system (Section 3.1.2.3), may follow. The developed design method already delivers all needed information to do so, such as production operations, assembly precedence graphs, and processing times.

The system design team of the validation partner outlined that it appreciated the simplicity of methods and tools as well as the fact that the members were able to collect all needed data themselves. The generated production process analyses and documentations were also considered useful for future production system optimization projects. The referenced production system model was found to be helpful. The members of the team named the structured approach and the clear dedication of the each design phase (i.e. each mapping between design domains) to results and intermediate design embodiments as the strongest advantages of the developed design method.

8 Conclusion and outlook

The new paradigm of **personalized production** brings about a **high number of product variants** to be produced in a **volatile business environment**. Production systems need to be flexible and reconfigurable to produce multi-variant production programs efficiently in scalable output volumes. **Matrix production systems** are a promising concept for personalized production. Their modular architecture of flexibly linked process modules makes the system reconfigurable. The flexible linkage of process modules allows the production of a wide range of product variants in the same production system, in an almost arbitrary variant mix. So far, however, no sufficient methods existed for a systematic design of matrix production systems.

Established production system design methods are tailored to create production systems for specific product variants and a specific range of output quantities. Initiatives for the design of changeable assembly systems focused on the optimization of lean production lines. The fixed sequence of operations and the loss of productivity, due to cycle time variations, persisted. FMS, RMM and BAZ, on the other hand, are machine-level developments to achieve flexible and reconfigurable machining technology production resources. Likewise, methods for the design of RMS focus mainly on machining technologies and do not consider the specifics of assembly.

Matrix production systems are able to combine manufacturing and assembly technologies in one production system. Existing methods to design matrix production systems, however, only focus on assembly operations. The product architecture of given variants and a defined range of output quantities are used as input variables of the design. Similar to lean line design, they pursue product- and capacity-driven design processes.

All in all, existent methods are either tailored to assembly or machining technologies only or do not dissolve a fixed coupling of production resources in the production system.

This dissertation states the **hypotheses** that a *modular matrix production system* of flexibly linked process modules (Hypothesis 1) and a *process-driven design approach* (Hypothesis 2) are suitable for personalized production system design. An according **design method** is developed and **embedded** into a **methodical design system** which also contains a **reference model** and an **evaluation method**. The design method is based on Axiomatic Design (AD) to ensure a systematic and structured design process and to give guidelines to a production system designer on how to achieve a good design through the adaption of AD's axioms and corollaries. The reference model conveys the basic system setup to the system designers. Furthermore, it builds a framework for the design method itself by decomposition of the overall process into expectable intermediate results by assigning the different components of the method to partial models and by the specification of design parameters. The evaluation method allows for a comparison of different design embodiments for their suitability to fulfill overall productivity KPIs and a required output in different variant mix scenarios. Material flow simulation is applied as a tool for the evaluation method.

The **original version** of the design method of **AD** structures the design process into four design domains connected in series. The customer domain collects the design goals as CA. The functional domain translates these design goals into FR. The physical domain maps (physical) DP_i as design solutions to each functional requirement. The process domain, finally, assigns PV_i to each design parameter and, thus, characterizes a process to realize the specified DP_i. The FR-DP and DP-PV mappings between the design domains are accompanied by a decomposition process, which breaks down each requirement in line with the original design intent, until a final design stage is reached with a design that can be implemented. AD promotes a separation of system functions (Independence Axiom) by independent design solutions for each functional requirement. For the selection of alternative design solutions, AD offers a decision making criterion (Information Axiom) which states to always select the solution that has the highest probability to fulfill the requirements, taking into consideration tolerance-related deviations of the solution properties. AD expresses this success probability by the information content I of a solution-to-requirement mapping. AD deduces corollaries and theorems from its axioms to give further guidance to the designers on how to achieve a good design.

The **developed methodical design system of this dissertation** puts the **functional process module design** before the **overall system design**. Manufacturer-specific, functionally pre-instanced process modules are configured by the process module design. The system design selects and instantiates these functionally pre-instanced process modules.

Process modules are function-bearing elements of a production system. When instanced in a production system, a process module executes certain processes of the production system. By designing the process modules first, a **process-oriented design approach** is established. This process-driven approach allows for the creation of a system's functional concept, independent of specific variants and output quantities, and a subsequent instantiation of the system functions under consideration of an actual production program, thus establishing the hierarchical and structural system concept after the functional system concept.

AD's systematic mapping of design domains is maintained for the process module design. The design parameters are assigned as follows:

- CA represent the production operations.
- FR characterize the functional process needs of the operations.
- DP represent the processes of the production system.
- PV represent the physical elements of a production system.

The clusters of production operations per CA_i are built according to the change barriers of the production system. Change barriers are technological, technical or organizational limitations of a process. Effectively, a change barrier prevents a fully functionally integrated process module which would be capable to execute all required manufacturing and assembly processes of a manufacturer. The identification of relevant change barriers is a business knowledge-intensive process, strongly dependent from the state of the art of technologies and technical and organizational developments. Whenever a technological, technical or organizational solution is conceivable that enables to integrate different operations into one cluster, there is no change barrier considered to be effective.

The change barrier analysis simplifies the clustering of production operations, as it does not require a complete description of functional process requirements, but only identifies the smaller number of constraining process boundaries that are shared by operations. More importantly, the change barrier analysis allows to integrate different operations into one cluster that require different manufacturing or assembly technologies or technical equipment, but do not necessarily require to be processed on different process modules.

The clustering of production operations is not influenced by their affiliation to certain product variants, but purely focuses on the process requirements of an operation and its relevant change barriers, in relation to all other operations. The FR for the process module design is qualified on the basis of all operations contained in one cluster. The clustering thus specifies the functional capabilities of the production systems' process modules. It lays the foundation for the functional segmentation of a matrix production system during a specific production system design project.

Each FR is mapped with a process DP hierarchy from the reference model. A manufacturer-specific knowledge base of functions is built, to span a solution space for the configuration of process modules. The knowledge base contains potential production system elements PV_i, specified by their system ranges of functional abilities, and associates them to specific processes DP_i of the production system. AD's calculation rules for the calculation of the information content I were expanded to cover the selection of design solutions for a spread of requirements, as prevalent for the design of a process module which has to be flexible to execute all operations clustered within a CA_i. The

DP-PV mapping results in a knowledge base of functionally pre-instanced process module configurations.

The developed **method for overall system design** selects a process module configuration out of the knowledge base for each actual and planned operation of a production system design project. The functional fit of process modules is considered through the comparison of system and design ranges of flexibility, reconfigurability and functional process ability. Relevant AD corollaries are associated to each step of the selection process to be effective as design guidelines. Selected PV_i are instantiated as Process Modules (PMs) of the production system, to fit the actual capacity requirements of a production system design project. Subsequently, the design processes for material flow, material supply, order sequence and capacity control processes, and a material flow-oriented layout are specified.

The **developed evaluation method** evaluates each design embodiment according to its achievement in respect to project-specific constraints, to changeability and to productivity with specified KPIs. To evaluate dynamic parameters, material flow simulation is applied. The system design method contains the option to iterate to the process module design, eventually separating formerly coupled production operations of a CA_i clusters, in order to achieve an overall result that is more compliant with given constraints such as available space or a maximum possible amount of investment.

A **matrix production system**, designed with the developed methodical design system, contains several PMs of different functional scope. The process-oriented, change barrier-driven segmentation creates PMs, that can be distinguished by their technology, their technical equipment, or by specific organizational or infrastructural requirements. PMs are specialized if they contain certain technical equipment that cannot be integrated or operated with other equipment if the union of different material flows makes an automated PM of a specific function economically feasible or if built-in high-investment equipment or high operational cost of a PM require a high utilization of a specific functions. Non-specialized PMs, on the other hand, integrate multiple functions for a variant-universal execution of processes. A PM may be a single instance of a functionally pre-instanced PV_i, or it may be one of multiple instances of the same functional scope, to cover differing capacity needs of different function. To ensure a high and balanced utilization of operations, the system design method introduces multiple machine operation and individual run times of PMs to its matrix production concept. On PMs with multi-process ability, an order is processed as long as possible. It is only transported to the next PM if all production operations are executed that the prevalent PM is functionally capable to execute, in dependence of the precedence of operations. The transportation of goods through the system and the material supply are likewise realized by material flow PMs, which are designed by the same manner as their value-add counterparts, triggered by a clustering of transportation operations. Matrix production systems are able to integrate all needed processes to produce a wide range of product variants into one production system.

The **guiding research question** of this dissertation, how to design production systems so that they meet the requirements of personalized production, **is answered** by the developed methodical design system. The matrix production system which was designed for the validation project of this dissertation showed a high product flexibility and system reconfigurability and achieved a higher output, better values of productivity KPIs, and a higher capacity flexibility in the system evaluation than the validation partner's status quo production system. It also scored higher than a compared hybrid production system design embodiment, which included a lean line design for some of the validation case's operations. The system simulation was carried out with a real, past, representative production program of the validation partner, loaded with an actual customer order's sequence. **The hypotheses** that a modular system architecture of flexibly linked process modules (Hypothesis 1) and a process-oriented design approach (Hypothesis 2) are suitable for personalized production system design, can, therefore, **be approved positively**.

In summary, this thesis delivered a methodical system for the design of matrix production systems for the personalized production of mechatronic machine modules. The main focus was the segmentation of system functions on value-add and material flow process modules and their capacity-considerate instantiation and relation. A technical design of process module elements, the production order control processes, and the material supply systems are only detailed in the methodical system to the extent to which they have an impact on the overall system design. Further research is consequently needed in these fields.

Subsequent research should address the detailed technical design of matrix-capable, reconfigurable assembly and manufacturing process modules. This includes a modular mechanical design and a standardization of interfaces between value-add process modules and the material flow. A focus must likewise be put on the self-description and connection of process modules, in order to accomplish the information exchange between them and the superordinate system level.

The setup of matrix production system creates a complex job shop scheduling problem. The dissolution of fixed order sequences and the uncertainties of the time of actual order processing and order distribution onto different PMs, furthermore, challenges material supply systems. Material requirements can only be predicted upfront to a very limited extent. Methods and algorithms for an optimal scheduling and control of production orders in a matrix production system are needed. Research in this field needs to also address the question of whether an ad-hoc control strategy produces better results than a pre-determined sequence of PMs per production order. The actual state of the overall system and of individual PMs in the system, scheduled shutdowns, interdependencies to the supply chain, and the consideration of system reconfigurations are of major importance. Moreover, flexibility and reconfigurability of a matrix production system can only be fully exploited if matrix-capable material supply strategies are available. There is a need to forecast material requirements at individual PMs of the production system, incorporating system states and the control logic of the system.

The modular setup of matrix production systems offers the possibility of frequent reconfiguration to optimize the system's point of operation. Due to the complexity of a matrix production systems, it may be difficult to identify optimization potentials and reconfiguration needs by expert knowledge. Methods and analytical frameworks for system monitoring and decision-making models for reconfiguration are required.

Full-scale implementation of matrix production systems has, furthermore, implications for product and process development. The importance of modularity in product design will further increase and the implementation of adaptive manufacturing process chains is fostered.

Finally, a benefit-oriented benchmark of different production system concepts and transformation scenarios are needed to support the transformation of existing production systems into matrix production systems.

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A List of symbols

A	Area consumption
$A_{cr,i}$	Common area under the system probability density function, within the common range cr of a requirement-solution mapping i
C	Design constraint
CA	Vector of customer attributes of a design
CA_i	Customer attribute i of a design; parameter of CA
cp_i	Common point of a design and system range, or design and system point, of a $FR_i - DP_i$ or $DP_i - PV_i$ mapping
CP	Set of common points
cr_i	Common range of a design and system range, or design and system point, of a $FR_i - DP_i$ or $DP_i - PV_i$ mapping
CT	Cycle time
DP	Vector of design parameters of a design
DP_i	Design parameter i of a design; parameter of DP
dr_i	Required design range of an FR_i
$\mathrm{dr}_{is,i}$	Permissible tolerance range, describing an actual allowable tolerance range of an FR_i
$\mathrm{dr}_{future,i}$	Permissible tolerance range, describing a future allowable tolerance range of an FR_i
fdp_i	flexible design point, describing an actual required flexibility potential of an FR_i
FDP	set of flexible design points
fdr_i	Flexible design range, describing an actual required flexibility potential of an FR_i
FR	Vector of functional requirements of a design
FR_i	Functional requirement i of a design; parameter of FR
fsp_i	Flexible system point, describing an actual flexibility potential of a DP_i or PV_i
FSP	Set of flexbile system points
fsr_i	Flexible system range, describing an actual flexibility potential of an FR_i
I_i	Information content of a $FR_i - DP_i$ or $DP_i - PV_i$ mapping
I_{Sys}	Information content of a $FR - DP$ or $DP - PV$ mapping of a complete system design
I_{is}	Information content of a $FR_i - DP_i$ or $DP_i - PV_i$ mapping regarding an actual permissible process deviation
I_{future}	Information content of a $FR_i - DP_i$ or $DP_i - PV_i$ mapping regarding a future permissible process deviation

I_{flex}	Information content of a $FR_i - DP_i$ or $DP_i - PV_i$ mapping regarding a current flexibility of a design
$I_{reconfig}$	Information content of a $FR_i - DP_i$ or $DP_i - PV_i$ mapping regarding a future flexibility of a design, achieved through system reconfiguration
$I_{changeability}$	Information content of a $FR_i - DP_i$ or $DP_i - PV_i$ mapping regarding current adn future flexibility of a design
Invest	Investment cost
Ω	Universal set of same-function systems, available on the market as design solution
p_i	Success probability of a $FR_i - DP_i$, or $DP_i - PV_i$ pairing
p_{flex}	Success probability of a $FR_i - DP_i$, or $DP_i - PV_i$ pairing, regarding actual flexibility requirements and potentials
$p_{reconfig}$	Success probability of a $FR_i - DP_i$, or $DP_i - PV_i$ pairing, regarding future flexibility requirements and potentials, achievable through system reconfiguration
PM_i	Process module instance i
PT_{mean}	Mean processing time per unit
PV	Vector of process variables of a design
PV_i	Process variable i of a design; parameter of PV
rdp$i$	Reconfigurable design point, describing a future required flexibility potential of an FR_i
RDP	Set of reconfigurable design points
rdr_i	Reconfigurable design range, describing a future required flexibility potential of an FR_i
rsp_i	Reconfigurable system point, describing a future flexibility potential of a DP_i or PV_i, achieved through system reconfiguration
RSP	Set of reconfigurable system points
rsr_i	Reconfigurable system range, describing a future flexibility potential of an FR_i, achieved through system reconfiguration
SD	standard deviation
SF	Safety factor
sr_i	System range of a DP_i or PV_i
$sr_i s, i$	System range, describing an actual tolerance range of a DP_i or PV_i
sr_{future}	System range, describing a future tolerance range of DP_i or PV_i, achieved through system reconfiguration
TT_{mean}	Mean transport time

B Production system hierarchies and common production KPIs

VDI 5200-1 (p. 6)	Förster et al. (1982, p. 31)	ElMaraghy et al. (2009, p. 11)	Schenk et al. (2014, p. 165)	Westkämper et al. (2009a, p. 61)
Network		Network	Network	Network
Plant	Plant		Site	Site
Building		Factory	Factory	
Segment	Segment	Segment	Segment	Segment
	Section	System	Coupled Stations	System
	Group	Cell		Cell
Station	Station	Station	Station	Station/Machine

Table B.1: Production system hierarchies (1/2)[148]

Löffler (2011, p. 15)	H-P. Wiendahl (2005, p. 22)	T. Heinen et al. (2008, p. 21)	Rauch (2013, p. 49)	Car et al. (2004, p. 20)
Network	Network	Network	Network	Micro ecosystem
Site	Site	Plant	Enterprise	
	Factory	Factory	Factory	Factory
Segment	Segment	Segment	Segment	
System/Line	System		Cell/Line	Floor
Cell/Section		Station	Process Units	Cell
Station/Takt	Station	Machine	Stations	
Process	Process	Modules	Ribosome	

Table B.2: Production system hierarchies (2/2)[148]

[148]The literature review for this overview was done by C. Galm at Fraunhofer IPA in 2015 for his mid-term thesis.

	KPI	Definition	Source
Operative performance	Production Output	No. of articles or orders produced per time interval	H-H. Wiendahl (2011, p. 139)
	Throughput Time	Time span between start and end of an order or process	ibid., p. 111
	Work In Process (WIP)	Inventory inside a production system within a time interval	ibid., p. 112
	Mean Inventory	Mean number or value of articles in stock	Bungartz (2012, p.369)
	Days of Inventory	Ratio of mean inventory and mean daily consumption	
	Overall Equipment Effectiveness (OEE)	Utilization of a production resources within a time interval (*availability · performance · quality rate*)	Shirose (1992, p. 53)
	Scrap Rate	Percentage of rejects from total output	VDMA 66412-1 (p. 29)
	Rework	Percentage of rework from total output	
System structure characteristics	Overall Capacity	Total number of production hours (personnel and machine resources)	Bungartz (2012, p. 374)
	Minimum Economic Lot Size	Ratio of fixed cost and margin of a production order	ibid., p. 372
	Degree of Automation	Ratio of automated and total number of processes	ibid., p. 373
	Personnel Qty.	Number of employees needed for operation	Brankamp (2014, p. 34)
	Machine Qty.	Number of machines in the system	
	Capital Investment	Investment volume per time interval	
	Fixed Assets	Sum of all fixed asset costs	
Productivity	Personnel Productivity	Ratio of value add and personnel cost	Brankamp (2014, p.34)
	Fixed Assets Productivity	Ratio of value ad and fixed cost	
	Area Productivity	Ratio of value add and production area m^2	

Table B.3: Common production KPIs

C Axiomatic Design

C.1 Example of Axiom 1 application

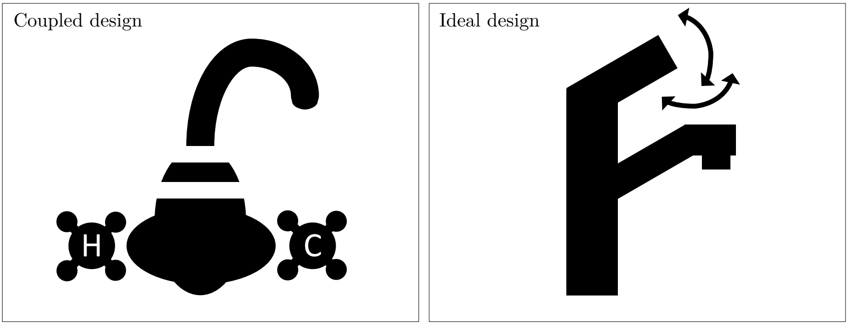


Figure C.1: Water faucet example of a coupled and an ideal design

A common example to explain the difference between an ideal and a coupled design is the water faucet example, introduced by Suh (2001, pp. 119–124). A water faucet has to fulfill two functional requirements:

- FR1 = control the water flow rate
- FR2 = control the water temperature

To explain Axiom 1, two different types of water faucets are compared (Figure C.1). The first type has two knobs to adjust the hot and cold water flow rate. The design parameters of this type of water faucet are respectively:

- DP1 = hot water knob
- DP2 = cold water knob

Even though there are two physical parts, the type with the two knobs is a coupled design. When turning either of the two knobs, both the water flow rate and the water temperature change. It is impossible to influence the two functional requirements independently. The design matrix of the design is a full matrix (Equation C.1).

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} x & x \\ x & x \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{C.1}$$

The second type has a handle bar which can be moved horizontally and vertically. Let's assume the design is such, that the horizontal movement only influence the water temperature, while the vertical movement only influences the water flow rate. The design then is an independent design, as it allows to fulfill the two functional requirements independently from each other. The design parameters of this type of water faucet are respectively:

- DP_1 = vertical movement of handlebar
- DP_2 = horizontal movement of handlebar

The design matrix of the design is a triangular matrix (Equation C.2).

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} x & 0 \\ 0 & x \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{C.2}$$

In a decoupled design, the water faucet had to be designed in such a manner, that the water temperature and flow rate can be changed indepently of each other, as long as a defined order to control the two is kept.

C.2 Example of Axiom 2 application

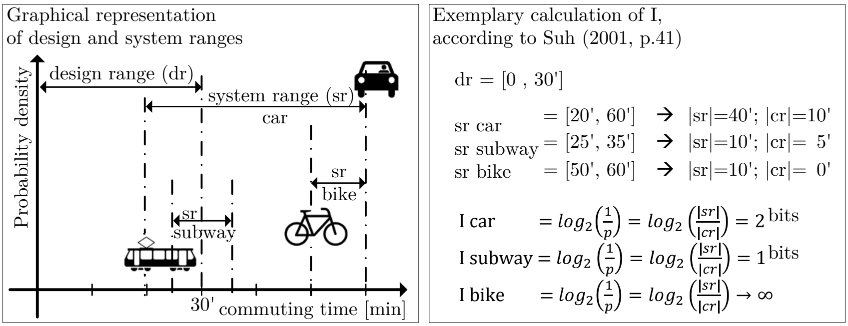


Figure C.2: Commuting time example to select successful design solution

Axiomatic Design's Axiom 2 states to select the design solution with the highest probability of success from alternative design solutions (Section 4.2.3). Here Axiom 2 is explained by the *FR-DP* pairing of a design parameter (DP_i) to a functional requirement (FR_i). FR_i state the design requirements, DP_i the design solutions. To estimate the highest probability of success a required design range of an FR_i is compared to the system ranges of each optional DP_i. The information content of each pairing expresses the likeliness of a design solution to meet the requirement.

As an example, a commuting time with different means of transport is compared (Figure C.2). To keep the example simple it is assumed that there is uniform distribution of possible commuting times within the given system ranges of the different transportation means.

It is required, expressed in the design range of the example, to achieve a commuting time of less than 30 minutes. In the example, it is impossible to meet this requirement with a bicycle, as it takes a system range of 50 to 60 minutes to commute the distance by bicycle. It is possible to achieve a commuting time of less than 30 minutes with both other DP_i, public transportation by subway, as well as a private car. But depending on delays and traffic, both means of transport bear the risk of exceeding the required maximum of 30 minutes. However, the calculation of the information content I for car and subway, according to Suh's calculation rules for a uniform distribution of design parameter values(Equation 4.5), shows, that commuting by subway has a higher probability of success (Figure C.2). I_{subway} is smaller than I_{car}. With the given uniform distribution of possible commuting times within the system ranges, the subway is expected to achieve the requirement 50% of the times. The spread of the car's system range is wider. Compared to the overlap of its system range with the design ranges, it is only possible to meet the requirement of less than 30 minutes commuting time by 25%.

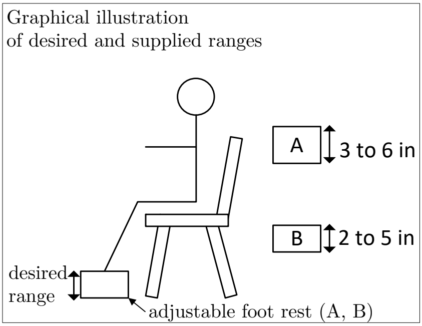
The commuting time example to Axiom 2 is valid, if the parameter values of the design solution are subject to a statistical distribution (Section 4.2.3). If, instead, the values of the required ranges are distributed statistically, the information content must be calculated according to the calculation rules introduces by Helander et al. (2002; 2007) (Equation 4.6). The following example of ergonomics design given by Helander et al. (2002, pp. 330–334) is introduced in the following.

For the design of an ergonomic workstation a hight-adjustable support for feet is to be designed (Figure C.3). Helander et al. (2002, pp. 330–334) identfify the according FR and DP:

- FR = support for feet
- DP = adjustable foot rest

By survey of their user group, Helander et al. (2002) defined a range of zero to five inches as desired range. This means, that the different human operators need a foot rest height in between zero to five inches, depending on their body size. To keep the example simple, an uniform distribution of required foot rest hights is assumed.

Two foot rests offered by two different manufacturers A and B were able to supply a system range of three to six inches (A), and two to five inches (B). According to Helander et al.'s calculation rules for ergonomics design, I_B is smaller than I_A and should thus be selected for the given user group.



Exemplary calculation of I, according to Helander et al. (2007, p.39)

desired range = [0, 5in]

supplied range A = [3, 6in] → |cr|=2 inch
supplied range B = [2, 5in] → |cr|=3 inch

$$I_A = log_2\left(\frac{|desired\ range|}{|common\ range|}\right) = log_2\left(\frac{|5|}{|2|}\right) = 1{,}32\ bits$$

$$I_B = log_2\left(\frac{|desired\ range|}{|common\ range|}\right) = log_2\left(\frac{|5|}{|3|}\right) = 0{,}73\ bits$$

Figure C.3: Ergonomics design example to select successful design solution

C.3 Corollaries of Axiomatic Design

Corollaries are defined by Suh (2001, p. 60), as follows:

- ***Corollary 1*** *(Decoupling of Coupled Design)*: Decouple or separate parts or aspects of a solution if FRs are coupled or become interdependent in the designs proposed.
- ***Corollary 2*** *(Minimization of FRs)*: Minimize the number of FRs and constraints (C).
- ***Corollary 3*** *(Integration of Physical Parts)*: Integrate design features in a single physical part if the FRs can be independently satisfied in the proposed solution.
- ***Corollary 4*** *(Use of Standardization)*: Use standardized or interchangeable parts if the use of these parts is consistent with the FRs and constraints (Cs).
- ***Corollary 5*** *(Use of Symmetry)*: Use symmetrical shapes and/or components if they are consistent with the FRs and constraints (Cs).
- ***Corollary 6*** *(Largest Design Ranges)*: Specify the largest allowable design range in stating FRs.
- ***Corollary 7*** *(Uncoupled Design with Less Information)*: Seek an uncoupled design that requires less information than coupled designs in satisfying a set of FRs.
- ***Corollary 8*** *(Effective Reangularity of a Scalar)*: The effective reangularity R for a scalar coupling matrix or element is unity. Compare Suh (1990, pp. 115–119) for the definition of reangularity.

D Supervised student theses

Lupberger, Severin, 2014: Modellierung von Wechselwirkungen zwischen Produktlebenszyklus, Technologielebenszyklus und Fabrikstruktur am Beispiel der Automobilindustrie (Modeling of interactions between the product life cycle, technology life cycle and factory structure on the example of the automotive industry).
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IFF, University of Stuttgart, Master's thesis

Wiedenmann, Marc, 2015: Analyse, Systematisierung und Bewertung von Betriebsmitteln im Automobilrohbau hinsichtlich ihrer Veränderungsfähigkeit (Analysis, systematization and evaluation of manufacturing equipment regarding their changeability in automotive body-in-white production).
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Burmeister, Anne, 2016: Tool zur Analyse der Montagedurchlaufzeit (Tool for the analysis of assembly throughput times).
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Eising, Jan, 2016: Simulationsbasierter Vergleich klassischer Linienmontage und alternativer Organisationsformen in der variantenreichen Serienproduktion (Simulation-based comparison of classical assembly lines and alternative organizational structures for serial production).
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IFF, University of Stuttgart, Bachelor's thesis.