Axiomatic design of matrix production systems

Petra Foith-Förster, Thomas Bauernhansl
Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, 70569 Stuttgart, Germany
petra.foith-foerster@ipa.fraunhofer.de

Abstract. Manufacturing companies are operating in a turbulent business ecosystem that demands for product variety, product mix flexibility, volume scalability and high efficiency. Personalized production arises as new production paradigm to replace mass personalization and changeable matrix production systems are well suitable to cope with the challenges of this new production paradigm. In this paper, a method to design the value-add process modules of a matrix production systems is presented. The method is based on Axiomatic Design. The approach works process oriented, pursues a modular layout, and a flexible material flow in the production system. The paper concludes with a validation of the method performed in an industrial use case.

1. Personalized production in turbulent business ecosystems
Just like the 1990s European housing crisis and the 2008 global financial crisis, the Covid19 pandemic caused a sharp decline in the industrial production indices of economies worldwide, which had otherwise constantly been growing [1]. Studies show that intervals between crises became shorter in recent decades [2]. Independent of economic crises, production systems face day-to-day production volume fluctuations, caused by product lifecycles, as well as by seasonal or random ordering behavior of customers. Consequently, the capability for structural upscaling, the ability to follow a day-to-day variation of volumes, and the possibility to downscale abruptly in times of crises and upscale quickly after a crisis gives a competitive edge to production systems.

Furthermore, the number of variants to be produced has multiplied in recent decades. Surveys conducted in the automotive and machine building industries in Germany showed that around 75% of all surveyed original equipment manufacturers (OEMs) and first-tier suppliers had raised their offered variants in the last ten years before 2004 [3] and plan to raise or even double the number of their physically offered variants until 2023 [4]. On top of that, multiple product generations are produced in parallel [5]. The new production paradigm of personalized production is introduced to meet this booming demand for unique products, individualized by a customer and ordered in a lot size of one [6].

All in all, the utilization of production equipment with a limited number of certain dedicated product variants becomes unlikely. Production volumes are difficult to predict and designing a production system for a fixed range of output numbers bears a high risks of over- or underutilized equipment. Manufacturing companies need to prepare for change in order to stay competitive and prosper [7].

2. State of the art and problem statement
Prevalent flexible manufacturing systems (FMS) and lean, mixed-model production lines with coupled stations and a defined cycle time are tailored for the previously effective production paradigm of mass personalization [6]. Neither FMS nor lean mix-model production lines provide enough flexibility and reconfigurability to prepare manufacturing systems with the needed changeability to tackle the
challenges of a personalized production in a turbulent business ecosystem. Instead, modular reconfigurable production system are promoted as a suitable setup for personalized production [6].

Early works on reconfigurable manufacturing systems (RMS) concentrated on the technological concepts for modular multi technology machines [8] and (autonomous) production modules [9]. Koren et al. introduced RMS on the production system level [10]. They investigated configuration and conversion of manufacturing systems [11], and general modular layout concepts of computer numerically controlled (CNC) machines [12]. The research group of ElMaraghy developed methods and algorithms for a periodic system configuration of capacity and functionality [13] and examined the topology of reconfigurable assembly systems (RAS) [14]. Albeit possibilities of using reconfigurable concept for assembly were examined [12], no methods to configure RAS exist so far.

Matrix production has been introduced as a concept of modular, reconfigurable production systems, built of flexibly linked process modules [15]. In a matrix production system, every variant processes through the system on its own, variant-specific path [15]. Process modules for the execution of the needed manufacturing and assembly processes are selected under consideration of process module functionalities, the possible sequence of operations and the current state of the system [15]. Existing methods on the design of matrix production have been developed for automotive assembly. Greschke [16] assigns assembly operations to process modules capacity-driven, aiming at an average system cycle time. Kern et al. [17] determine the functional scope of process modules with the help of an assembly precedence graph, considering variant-specific options. Neither of the two analyze production operations by their process characteristics, which could be applied to identify a possibility for functional integration of different operations, independent of the assembly sequence, to e.g. achieve a high utilization of investment-intensive or automated equipment.

Personalized production systems unite assembly and machining processes to realize the individualization of products as demanded by customers [18]. Assembly is very much affected by the increase of product variety and market turbulences, due to its proximity towards the customer in the value-creation chain [19]. Furthermore, the diversity of processes and tools is often higher in assembly than in machining, which restricts process integration and automation. Therefore, methods for the configuration and design of modular production systems for personalized production need to consider the specific requirements of both, machining, and assembly processes.

This paper presents a method to design matrix production systems with a process-driven approach for the functional segmentation of process modules and details the design of the value-add process modules. The method considering both manufacturing and assembly processes. To ensure a systematic and requirement-considerate design, Axiomatic Design (AD) is chosen as basic design method.

3. Introduction to Axiomatic Design

Axiomatic Design (AD) is a design methodology which guides the design process of complex technical systems with two fundamental axioms: The independence axiom (Axiom 1) seeks for functional separation of requirements and solution parameters. A design solution is considered ideal, if requirements are solved independently, i.e. each design solution only influences exactly one requirement. The information axiom (Axiom 2) delivers a decision-making principle between alternative design solutions by judging on their probability to successfully satisfy a respective requirement. The best design solution is considered the one with the least information content (I). [20]

AD proceeds through four design domains during the design process: The customer domain states the design goals, given as customer attributes (CA). The functional domain derives the functional requirements (FR) of the design from the CA. The physical domain maps design parameters (DP) to each FR. The process domain contains process variables (PV), which specify the needed parameters to realize the DPs. In addition to FRs, superordinate requirements, called constraints (C), set bound to possible solutions. Usually, a design needs to be completed before it can be checked regarding its Cs. During each mapping between two subsequent design domains, a design is detailed by decomposing each design state hierarchically into the next layer of requirements and design solutions, until an implementable design stage is reached. [20]
4. Axiomatic design method to design matrix production systems

The presented method proposes a two-phases matrix production system design process (Figure 1).

The first phase follows AD along its four design domains for the design of process modules. In this phase, the system hierarchy and the system’s functions are determined by decomposition of reference manufacturing, assembly, and material flow processes. Reference processes are derived from actual and conceivable future production operations. As a result of the process module design, functionally pre-instanced process module configurations are saved in a knowledge base of process modules. They are kept available for an initial system design as well as for later system reconfiguration designs.

In the second phase, process modules are selected from the knowledge base of process modules 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 AD design parameters are assigned as follows:

- CAs represent the production operations.
- FRs characterize the functional process needs of production operations.
- DPs represent the actual processes of the production system, to execute the production operations.
- PVs represent the physical elements of a production system. On the topmost level, PV is a functionally configured process module.
- PM are process module instances of PVs.
- C represent the overall design constraints.

Both, the process module design as well as the project-specific production system design are checked for independence with Axiom 1 whenever a design solution is mapped. The method allows for a systematic design of alternative production system design embodiments. To support the decision-making of the production system designers, AD axioms and selected corollaries are provided in the method. For the final decision on one overall system design embodiment, defined cost and productivity key performance indicators (KPIs) are used as input constraints for the design. Finally, the method contains a comparative evaluation to judge on the best overall design. Discrete event material-flow simulation is suggested to estimate dynamic parameters of the production system for the KPI calculation.

The two-phases approach decouples the design of a system’s functional concept from the design of output volumes and the consideration of variant-specific operation sequences. By doing so, the method helps the designer to achieve a flexible matrix production system, instead of limiting flexibility through a variant- and volume-driven segmentation of production operations.

This paper describe the method and the design process for the functional configuration of value-add manufacturing and assembly process modules, and their instantiation in an overall system design. The design of material flow process modules, the related selection of material supply strategies and buffer dimensioning, as well as the design of a production control process, are not part of this paper.
4.1. Process module design

4.1.1. Process module design goal clarification (CA-FR). Following the design process of AD, the clarification of the design goals is the very first step to achieve a successful design. Design goals are derived from CAs. The CAs of the process module design relate directly to the respective manufacturing and assembly operations, needed to produce certain reference products (Figure 2).

CAs cluster similar production operations. The subsequent design process designs a process module for each CA. Consequently, it must be conceivable that all operations of one cluster may be successfully executed through identical instances of production resources.

![Figure 2: Operations matrix for the clustering of production operations as CAs](Image)

To identify CA clusters, a change barrier analysis delivers the sorting criterion. A change barrier is defined as a category, by which the limits of use of a technical system can be quantified [21]. 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. If there are technical, technological or organizational solutions conceivable, so that it seems possible to functionally execute all customer-specific manufacturing operations on one manufacturing process module and all assembly operations on one assembly process module, there are no relevant change barriers. 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. Very often, automation is 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 automated production cells.

Each CA is assigned with a FR in a one-to-one mapping. The CA-FR mapping delivers the design ranges for each CA. Each design range covers the individual values or ranges of all clustered operations. Design ranges are specified in the dimensions of change barriers. There is one design range per change barrier for each CA.

The specification of design ranges differentiates between ranges that describe a permissible tolerance and ranges that are associated to flexibility and reconfigurability requirements (Figure 3). Design ranges of flexibility and reconfigurability are specified by unifying the ranges of clustered operations in a so-called changeability design range. Design ranges of permissible tolerances are specified by intersection of the ranges of clustered operations in a so-called process capability design range.
There are four AD corollaries that are relevant to the process module design goal clarification:

- **Corollary 1 Decoupling of coupled designs**: The CA-FR mapping must result in collectively exhaustive and mutually exclusive (CEME) \([22]\) FRs, i.e. disjunct clusters of operations.
- **Corollary 2 Minimization of FRs**: An integration of a large number of multiple operations into one cluster of CEME CAs must be pursued by design.
- **Corollary 6 Largest design ranges**: An integration of multiple operations to achieve a broad range of (changeability) design ranges must be pursued by design.
- **Corollary 7 Uncouple design with less information**: If a conceivable solution exists that covers the design ranges of previously separated CAs, these CAs must be united.

### 4.1.2. Process Module hierarchy (FR-DP)

The FR-DP mapping assigns and decomposes processes to each FR. The mapping effectively ensures, that all needed processes and activities are incorporated into a value-add process module to successfully execute all operations clustered in the associated CA.

A generic process module hierarchy was published as a reference model for process module design in a previous paper \([16]\). For the FR-DP mapping, an appropriate reference hierarchy must first be selected from the model. The system designers need to review the selected model’s FR-DP design tree. The design tree needs to be checked for independence, relative to the requirements of clustered operations. Functional necessities may require for an 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. There are three principal reasons for an adaption (Figure 4):

1. **Operation-specific process requirements**: The reference model is built to generically fit any production technology. Depending on the project-specific technologies, it is possible that certain branches of the reference’s model FR-DP design tree can be eliminated or must be duplicated. **Example**: A screwing process does not produce residue. The *eject residue* activity is deleted.

2. **Coupled FRs**: FR may be coupled due to technological constraints. In this case, a production operation associated to one FR cannot be successfully executed independent of a second operation associated to a different FR. The result is a lack of factory load case readiness. There is no feasibility of a material flow between coupled processes, and the respective process module instances cannot be separated spatially in the production system design. **Example**: Heating and shrinking operations might be clustered in different CAs, but must be designed as decoupled process for a successful execution of the shrinking operations.

3. **Integrated CAs**: As an alternative to couple FRs, it is possible to iterate into the cluster definition and split the specific production operations into separate CAs. This results in an ideal design, when an according FR integrates both the dependent operations. The FR-DP design tree needs to be functions-integrative, ultimately adapting the design tree with additional activity branches. **Example**: Instead of separate clusters for heating and shrinking, an integrative CA is built to cluster heating/shrinking operations separate of other heating and other pressing operations.
4.1.3. Process module configuration (DP-PV). The DP-PV mapping finishes the functional configuration of value-add process modules by mapping production system elements to each process and activity (Figure 5). Each fully configured process module is saved in a knowledge base of functions to be kept available for a subsequent production system design. Production system elements are kept available for the configuration in a manufacturer-specific knowledge base of functions. The knowledge base of functions contains a selection of (market-) available production system elements for each reference activity, as defined by the process module reference model. Production system elements are specified in the knowledge base by their system ranges in the dimension of change barriers, according to the design ranges introduced in section 4.1.1. A production system element is a production resource, such as a specific tool, robot, machine, workstation, material bin or even a human operator, specified by its specific knowledge, if operator knowledge was identified as a change barrier.

The PV selection is guided by AD’s Axiom 2. Conceivable solutions, that led to the clustering of operations into CAs, may not necessarily be selected. There might be economical or technological reasons to select another solution, or simply different alternatives are designed.

\[ I_{overall} = I_{process\text{-}capability} + I_{changeability} \]

\[ = -\log_2 \left| \frac{process\ capability\ common\ range}{process\ capability\ system\ range} \right| - \log_2 \left| \frac{changeability\ common\ range}{changeability\ design\ range} \right| \]  

(1)

Figure 4: Example process module hierarchy adaption

Figure 5: Process module configuration process
4.2. Production system design

Albeit the matrix production system must be designed reconfigurable to equip it for future developments in volatile business ecosystems, a functionally and capacity-wise fitting production system setup can only be designed under consideration of an actual or planned production program. As preliminary step to the production system design, this project-specific production program needs to be prepared and input C must be clarified.

To instantiate the value-add process modules of the system, the process-oriented design approach selects process modules from the knowledge base of process modules by function first, before considering capacity needs in the second step. The selection is a mapping of a process module to each individual production operation of the design project-relevant production program, considering its related process in the dimensions of change barriers.

For the actual selection, all value-add operations are compared to all PV from the knowledge base of process modules. A tabular display may be used for the comparison (Figure 6). The cells of the table contain the $I_{overall}$ of each pairing. The decision process is guided by AD’s Axiom 2 and Corollary 3 Integration of physical parts. According to Axiom 2, any production operation should be assigned to a process module, for which the mapping results in the smallest $I$. At the same time, the validity of Corollary 3 reduces the total number of different process module configurations in the production system. For an integration of different operations into one process module, the system designer should select the most universal process module (e.g. PV1 and PV8 in the example of Figure 6). It is nevertheless possible, to deliberately select different PVs for different operations, even though the same PV 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, even though a higher-universal manual PV would also be capable of their execution (e.g. operation 8 in the example of Figure 6). It is furthermore useful to separate operations with non-configuration options from highly configurable operations on different PV. During operation, orders with low configurations are then able to omit certain process modules, reducing the throughput time.

| value-add process module | PV1 | PV2 | PV3 | PV4 | PV5 | PV6 | PV7 | PV8 | PV9 |
|--------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| operation 1              |     |     |     |     |     |     |     |     |     |
| operation 2              |     |     |     |     |     |     |     |     |     |
| operation 3              |     |     |     |     |     |     |     |     |     |
| operation 4              |     |     |     |     |     |     |     |     |     |
| operation 5              |     |     |     |     |     |     |     |     |     |
| operation 6              |     |     |     |     |     |     |     |     |     |
| operation 7              |     |     |     |     |     |     |     |     |     |
| operation 8              |     |     |     |     |     |     |     |     |     |

$\bigcirc$ Lowest $I$ of operation-PV mapping

Figure 6: PV selection table for function selection of process modules

The CAs and FRs of the production system design can be concluded from the selection of process module configurations in the example of Figure 6 (Equation 2). From the mapping of the production operations, the FR-DP design matrices can be concluded (Equation 3).

\[
CA1 = \{op1, op3, op5\}; CA2 = \{op2, op4\}; CA3 = \{op6, op7, op8\}
\]

\[
\begin{bmatrix}
CA1 \\
CA2 \\
CA3
\end{bmatrix} =
\begin{bmatrix}
x & 0 & 0 \\
0 & x & 0 \\
0 & 0 & x
\end{bmatrix}
\left[
\begin{array}{c}
FR1 \\
FR2 \\
FR3
\end{array}
\right] =
\begin{bmatrix}
x & 0 & 0 \\
0 & x & 0 \\
0 & 0 & x
\end{bmatrix}
\left[
\begin{array}{c}
DP1 = PV1 \\
DP2 = PV2 \\
DP3 = PV3 \\
DP4 = PV4 \\
DP5 = PV5 \\
DP6 = PV6 \\
DP7 = PV7 \\
DP8 = PV8
\end{array}
\right]
\]
Only 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 a selected PV is 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 must be selected for the cluster. Both cases cause an iteration to previous design steps.

To address the differing capacity requirements of the production operations, a capacity harmonization of selected PVs is done and leads to the process module instances (PM) of the system design. The harmonization considers the overall capacity needs of a production scenario as well as the distribution of capacity needs between different system functions. The tabular display of functional suitability for process module selection may be advanced to judge on the average utilization of each selected PV (Figure 7). Whenever a utilization reaches a target value (e.g. set to 85% to cover overall equipment effectiveness (OEE) losses), a new instance of this respective process module PV must be added to split the capacity load.

The instantiation process results in a redundant design if one PM instance per PV is not sufficient to satisfy all capacity requirements of the assigned production operations (Equations 4 and 5). The redundancy adds to the system’s failure and routing flexibility. As the redundancy only occurs for PM instances, and the one-to-one FR-DP-PV mapping is kept, it does not violate AD’s Axiom 1.

\[
\begin{pmatrix}
PV1 \\
PV3 \\
PV8
\end{pmatrix} = 
\begin{pmatrix}
xxx0x0 \\
000x0 \\
0000x
\end{pmatrix} \begin{pmatrix}
PM1.1 \\
PM1.2 \\
PM1.3
\end{pmatrix}
\] (4)

\[
\begin{pmatrix}
CA1 \\
CA2 \\
CA3
\end{pmatrix} = 
\begin{pmatrix}
x00x0 \\
x00x0 \\
x00x0x
\end{pmatrix} \begin{pmatrix}
PM1.1 \\
PM1.2 \\
PM1.3
\end{pmatrix}
\] (5)
The utilization is an average value. It must be validated regarding its dynamic behavior in the system design evaluation. The harmonization table maintains the information about alternatives to the selected PVs. This enables an iteration to PV selection if an alternative assignment of production operations suggests the likelihood of a better harmonization.

The overall matrix production system does not run on a balanced system cycle time. Nevertheless, it is desirable to achieve a harmonized distribution of PM utilization. In a highly harmonized system, the overall work-in-process inventory (WIP) in the system’s buffers is reduced and all PM are able to operate simultaneously. The instantiation process of PMs doubles over-utilized PMs. This almost certainly leads to some under-utilized PMs. 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. There are two options to deal with under-utilization and disharmonizations:

1. Multi-PM operation: For manually operated PM, it is possible to share operators to prevent idle times of operators. Respective PMs need to be located close to each other, as the operator will have to traverse between them. Multi-PM operation is an excellent flexibility reverse, if space-availability is not a constraint. A scale up of volumes is possible by adding operators and changing from multi- to single-PM operation.

2. Individual run-times: Due to the flexible linkage of PM in the matrix production system it is possible to schedule individual run-times of certain PMs, if several same-function PM exist, or if certain PM are exclusively dedicated to specific, rarely required production operations. Due to the one-piece-flow concept of a matrix production system, temporary shutdowns of PMs must be considered in the buffer dimensioning of the PMs.

For the design of the layout, the modified triangle method [23], or other heuristic or analytical methods for factory layout design may be applied.

4.2.1. System 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 have 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 maximization of changeability and productivity are seen as general input constraints for a matrix production system design [16]. Actual maximum or minimum limits of productivity parameters, and further, project-specific constraints are defined in the data preparation for the design project.

For the evaluation of system changeability, the changeability system ranges of the overall system are compared in the dimensions of the change barriers and related to the product variants relevant to 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.

For the evaluation of productivity, personnel productivity, asset productivity, and area productivity are analyzed (Equation 6). Consumed area and investment costs are static parameters and can be obtained from the design embodiment documentation. Output quantities and the number of personnel depend strongly on the production program and the chosen harmonization strategy of the system. A static calculation is hardly possible. 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.

\[
\text{Area prod.} = \frac{\text{output} \times \text{qty}}{\text{area} \times \text{time} \ [m^2]}; \quad \text{Asset prod.} = \frac{\text{output} \times \text{qty}}{\text{fixed cost} \ [€]}; \quad \text{Pers. prod.} = \frac{\text{output} \times \text{qty}}{\text{personnel} \times \text{time} \ [€]} \quad (6)
\]

An overall system design evaluation is only possible if the system is designed altogether, including material flow process modules, raw material supply and production control processes.

5. Validation use case: matrix production system for servomotors design
The validation was done at a manufacturer of servomotors. The manufacturer offers motors with a modular product architecture which can be configured according to individual needs (e.g. power, inertia, brake) and which contain customer-individual parts (e.g. length of shaft, type of shaft-hub joint). The company is a rapidly growing small or medium-sized enterprise (SME) that continuously adds new product families to its portfolio. With high uncertainties of volume growth, product variants and customer requirements, a respectively flexible and reconfigurable production system was needed.

The analysis of all manufacturing and assembly operations revealed several technical and organizational change barriers (Table 1). It was considered important to enable automation, as only very few of the operations were designed for automation. Another important change barrier were the competencies of operators, as there were certain production operations that only certain operators were able to execute due to their experience or special process knowledge.

| Change barrier                  | Related product or process property         |
|--------------------------------|--------------------------------------------|
| Value-add automated assembly   | design of parts and processes              |
| High-investment equipment      | specific production technologies           |
| Competencies of operators      | specific process requirements              |
| Load limit of manipulators     | weight of parts                            |

From the change barriers, 13 clusters of value-add operations were identified as CAs at first. After the FR-DP analysis, two more CA cluster were built by separation of existing clusters, to resolve a coupling between oven and shrinking processes (Table 2).

To build 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 and reconfigurability 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 and mechanical bench power presses.

| Operations                      | FR changeability specification | FR process capability |
|--------------------------------|--------------------------------|-----------------------|
| CA1 Turning operations          | dtech = \{turning\};           | Dimension tolerances  |
|                                 | dcomp = \{machinist\}         |                       |
| …                              | …                              | …                     |
| CA8 Balancing operations heavy rotor | dweight = [3kg,7kg];           | Measure precision    |
|                                 | dtech = \{balancing\};         |                       |
|                                 | dcomp = \{balancing routine\}  |                       |
| CA9 Balancing operations light rotor | dweight = [0kg,3kg];           | Measure precision    |
|                                 | dtech = \{balancing\};         |                       |
|                                 | dcomp = \{balancing routine\}  |                       |
| …                              | …                              | …                     |
| CA13 Light manual assembly & press | dweight = (0kg, 10kg);          | …                     |
|                                 | dpress = (0,25kN);             | …                     |
|                                 | dtech = \{other joining\};     |                       |
| …                              | …                              | …                     |

*other joining = \{screwing, inserting, circlip, pressing, wire prep, cleaning, labeling, lubrication, adjust\}

\(\text{dr}…\text{design range}\)
For the system design of the validation project, functionally pre-instanced process modules were configured from the knowledge base of functions and saved in a knowledge base of process modules. For many of the configured process modules, the existing machinery and equipment of the manufacturer were incorporated to reduce overall needed investment.

To achieve a capacity harmonization of PMs, a combination of multi-PM operation and individual run times was selected as a harmonization strategy of the validation project. The design of the validation project foresees three different strategies to implement multi-PM operations:

1. Single operator, multiple PMs: One operator is responsible for more than one functionally independent PM. The operator himself 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: 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: 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.

An ideal layout was created using the modified triangle method. The ideal layout was adapted to the building restrictions of the validation partner. The result was a U-shaped main material flow from the warehouse to the wrapping area, with the warehouse and the preassembly areas forming one flank of the U and the main assembly, testing, painting and wrapping areas forming the second flank (Figure 8).

The matrix-design embodiment of the validation project achieved better KPI values of personnel and area productivity than the validation partner’s status-quo production system setup and an acceptable asset productivity. The denominators (number of operators, investment, usage of production area) for the calculating of productivity KPIs were derived from the layout and the design documentation. The dynamic parameter of output quantity was determined with the help of a discrete material flow simulation model, mapping the current status quo of the validation partner’s production system and the two design embodiments of the validation project.

Figure 8: Validation case production system layout.
6. Conclusion and outlook

The paper presented a design method for the design of value add process modules for matrix production systems, to tackle the challenges of personalized production in a turbulent business environment. Matrix production systems are able to integrate all needed processes to produce a wide range of product variants into one production system. The presented method puts the functional process module design prior to the overall system design, to allow for a process-driven design approach and the creation of a system’s functional concept independent of specific variants and output quantities.

A matrix production system, designed with the presented method, contains several process modules of different functional scope in a modular layout, linked by a flexible material flow. Value-add process modules can be distinguished by their technology, their technical equipment or by specific organizational or infrastructure requirements. They 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 process module economically feasible or if built-in high-investment equipment or high operational cost of a process module require a high utilization of a specific function. Non-specialized value-add process modules, on the other hand, integrate multiple functions for a variant-universal execution of processes. A process module may be a single instance of a functional process module type, or it may be one of multiple instances of the same functional scope, to cover differing capacity needs of different functions. To ensure a high and balanced utilization of operations, the system design method introduces multiple machine operation and individual run times of process modules to its matrix production concept. On process modules with multi-process ability, an order is processed as long as possible. It is only transported to the next process module if all production operations are executed, that the prevalent process module is functionally capable to execute, depending on the precedence of operations.

The main focus of the paper was the segmentation of system functions and their capacity-considerate instantiation and relation as value-add process modules. A technical design of process module elements, the production order control processes, and the actual design of the material supply systems are not part of the paper. Further research is consequently needed in these fields.

List of used symbols and parameters

| Symbol | Definition |
|--------|------------|
| CA     | Customer Attributes as defined by Axiomatic Design. In the presented method, CA represent a cluster of production operations. |
| FR     | Functional Requirements as defined by Axiomatic Design. In the presented method, FR quantify the functional process needs of the clustered production operations. |
| DP     | Design Parameters as defined by Axiomatic Design. In the presented method, DP represent the actual processes and activities to execute the production operations. |
| PV     | Process Variables as defined by Axiomatic Design. In the presented method, PV is a functionally configured process module. |
| PM     | A process module instance of a PV. |
| PT [time] | Process time, quantifying the duration of a process or production operation. |
| operation n; n ∈ {1,…,K} | Specific production operation of a production system design project, with n as an integer value. |
| Ioverall | Overall information content of a requirement-solution pairing. |
| Iprocess-capability | Information content of a requirement-solution pairing, quantifying the fulfillment of the permissible tolerance requirements. |
| Ichangeability | Information content of a requirement-solution pairing, quantifying the fulfillment of flexibility and reconfigurability requirements. |
| dr     | design range, quantifying the requirements of a design. |
References

[1] OECD, 2020 *Industrial production (indicator): Manufacturing / Construction: 2015=100, Q3 2020 or latest available* (OECD Publishing) URL: https://data.oecd.org/industry/industrial-production.htm Accessed on: 01/21/2021

The World Bank 2021 *Data: Manufacturing, value added (constant 2010 US$): World Bank National Accounts data, and OECD National Accounts data files.* (Washington D.C: The WorldBank) URL: https://data.worldbank.org/indicator/NV.IND.MANF.KD?end=2018&start=1990 Accessed on: 01/21/2021

[2] Koch P, Niemeier S, Faßbender H et al. 2010 *Willkommen in der volatilen Welt: Herausforderungen für die deutsche Wirtschaft durch nachhaltig veränderte Märkte* (Frankfurt am Main: McKinsey & Company) p.21

[3] Kinkel S 2005 *Anforderungen an die Fertigungstechnik von morgen: Wie verändern sich Variantenanzahl, Losgrößen, Materialeinsatz, Genauigkeitsanforderungen und Produktlebenszyklen tatsächlich?* (Karlsruhe: Fraunhofer ISI) Mitteilungen aus der Produktionsinnovationserhebung, 37. URL: https://www.isi.fraunhofer.de/content/dam/is/i/dokumente/modernisierung-produktion/erhebung2003/pi37.pdf Accessed on: 01/21/2021, p.3

[4] Luckert M, Schiffer M, Wiendahl H-H, Schölhammer O and Köpler J 2018 *Zulieferer vor der Zerreißprobe: Wie Zulieferer im Automobil- und Maschinenbau den Wandel durch Industrie 4.0 meistern können.* (Stuttgart: Industrie- und Handelskammer) URL: https://www.ipa.fraunhofer.de/de/Publikationen/studien/studie-zulieferer-zerreissProbe.html Accessed on: 01/21/2021, p. 27

[5] ElMaraghy H and Wiendahl H-P 2009 *Changeability - An Introduction* In: ElMaraghy H (ed.): *Changeable and Reconfigurable Manufacturing Systems* (Guildford: Springer London) pp. 3–23, ISBN 978-1-84882-066-1, S. 6

[6] Koren Y 2010 *The global manufacturing revolution: Product-process-business integration and reconfigurable systems* (Hoboken: Wiley) ISBN 978-0-470-58377-7, S. 33-37

[7] Bauernhansl T and Mieche R 2020 *Industrielle Produktion - Historie, Treiber und Ausblick* In: Bauernhansl T (ed.): *Fabrikbetriebslehre 1: Management in der Produktion* (Berlin, Heidelberg: Springer Vieweg) pp. 1–33, ISBN 978-3-662-44537-2, p. 24

[8] Abele E and Wörn A 2004 *Chamäleon im Werkzeugmaschinenbau: Rekonfigurierbare Mehrtechnologiemaschinen.* ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb 99 (4), pp. 152–156; DOI: 10.3139/104.100756, p. 152

Abele E, Versace A and Wörn A 2007 *Reconfigurable Machining System (RMS) for Machining of Case and Similar Parts in Machine Building* In: Dashchenko A I (ed.): *Reconfigurable Manufacturing Systems and Transformable Factories: 21st Century Technologies* (Berlin, Heidelberg, New York: Springer) pp. 327–339, ISBN 978-3-540-29391-0; p. 327

[9] Pouget P M 2000. *Ganzheitliches Konzept für rekonfigurierbare Produktionsysteme auf Basis autonomer Produktionsmodule* (Düsseldorf: VDI) Fortschritt-Berichte VDI Reihe 2, Fertigungstechnik, 537. Zürich, ETH, Diss., 1999; ISBN 3-18537-02-8

Drabow G 2006 *Modulare Gestaltung und ganzheitliche Bewertung wandlungsfähiger Fertigungssysteme* (Gärbsen: PZH) Berichte aus dem IFW, 2006-5. Hannover, Univ., Diss., 2006; ISBN 3-939026-13-1

[10] Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G and van Brussel H 1999 *Reconfigurable Manufacturing Systems* *Annals of the CIRP* 48 (2), pp. 527–540; DOI: 10.1007/978-3-642-20617-7 6629, p. 528

[11] Maier-Speredelozzi V, Koren Y and Hu S, 2003 *Convertibility Measures for Manufacturing Systems* *Annals of the CIRP* 52 (1), pp. 367–370; DOI: 10.1016/S0007-8506(07)60603-9, p. 367

[12] Koren Y and Shpitalni M 2010 *Design of reconfigurable manufacturing systems* *Journal of Manufacturing Systems* 29 4, pp. 130–141; DOI: 10.1016/j.jmsy.2011.01.001, p. 134-137
[13] Youssef A and ElMaraghy H 2006 Modelling and optimization of multiple-aspect RMS configurations. International Journal of Production Research 44 (22), pp. 4929–4958; DOI: 10.1080/00207540600620955

Youssef A and ElMaraghy H 2007 Optimal configuration selection for Reconfigurable Manufacturing Systems. International Journal of Flexible Manufacturing Systems 19 (2), pp. 67–106; DOI: 10.1007/s10696-007-9020-x

Navaei J and ElMaraghy H 2014 Grouping Product Variants based on Alternate Machines for Each Operation. Procedia CIRP 17, pp. 61–66; DOI: 10.1016/j.procir.2014.01.124

[14] Manns M, Urbanic R J and ElMaraghy H 2008 A Design Approach for Reconfigurable Assembly Systems. In: 2nd CIRP Conference on Assembly Technologies & Systems (CATS). Toronto, Canada, 09/21-23/2008, pp. 231–243

[15] Fries C, Fechter M, Ranke D, Trierweiler M, AlAssadi A, Foith-Förster P, Wiendahl H-H and Bauernhansl T 2021 Fluid Manufacturing Systems (FLMS) – A novel approach for versatility in production. In: Weißgräber P, Heieck F, Ackermann C (eds.): Advances in Automotive Production Technology – Theory and Application (Wiesbaden: Springer Vieweg) DOI 10.1007/978-3-662-62962-8

[16] Greschke P I 2016 Matrix-Produktion als Konzept einer taktunabhängigen Fließfertigung (Braunschweig: Vulkan) Schriftenreihe des Instituts für Werkzeugmaschinen und Fertigungstechnik der Technischen Universität Braunschweig. Braunschweig, TU, Diss., 2016; ISBN 978-3-8027-8344-9

[17] Kern W, Rusitschka F, Kopytynski W, Keckl S and Bauernhansl T 2015 Alternatives to assembly line production in the automotive industry. 23rd International Conference on Production Research (ICPR). Manila, Philippines, 07/31-08/02/2015, pp. 1–9; URL: https://www.researchgate.net/publication/317279321_Alternatives_to_assembly_line_production_in_the_automotive_industry, Accessed on: 01/14/2021

Kern W, Rusitschka F and Bauernhansl T, 2016 Planning of workstations in a modular automotive assembly system. Procedia CIRP 57, pp. 327–332; DOI: 10.1016/j.procir.2016.11.057

[18] Foith-Förster P and Bauernhansl T 2019 Generic Production System Model of Personalized Production. MATEC Web of Conferences 301, DOI: 10.1051/matecconf/201930100019

[19] März L and von Langsdorf P 2001 Flexibilität und Marktorientierung in der Montage In: Westkämper E, Bullinger H-J, Horváth P, Zahn E (eds.): Monteplanung - effizient und marktgerecht (Berlin: Springer) pp. 3–10; ISBN 3-540666-47-8, p. 3

[20] Suh N P, 2001 Axiomatic design: Advances and applications (New York: Oxford Univ. Press.) The MIT-Pappalardo series in mechanical engineering ISBN 0-195134-66-4

[21] Foith-Förster P, Wiedenmann M, Seichter D and Bauernhansl T 2016 Axiomatic Approach to Flexible and Changeable Production System Design. Procedia CIRP 53, pp. 8–14; DOI: 10.1016/j.procir.2016.05.001

[22] Brown C 2005. Teaching Axiomatic Design to Engineers - Theory, Applications, and Software. Journal of Manufacturing Systems 24 (3), pp. 186–195; DOI: 10.1016/S0278-6125(06)80007-5; p. 189

[23] Schmigalla H 1968 Methoden zur optimalen Maschinenanordnung (Berlin: Verlag Technik)