Challenges of Mechatronical Engineering of Production Systems: An Automation System Engineering View

Arndt Lüder and Nicole Schmidt

Abstract The importance of quality and efficiency of engineering process for production system is continuously increasing. Engineering sciences are encouraged to improve its tool and method sets to face this challenge. But in several cases engineers are not the real specialists for improving the toolbox of engineering. Here mathematical science can assist engineering sciences.

Within this paper open research issues for mathematical sciences are derived from the current state of the art in mechatronical engineering of production system intending to encourage joined research activities of mathematical and engineering science.

1 Introduction

The increasing global competition between companies from different global regions with completely different economical conditions forces European companies on the one hand to increase product variety, often until complete individualization to meet customer needs. In parallel, on the other hand, these companies are encouraged to increase production system flexibility regarding resource capabilities and quantities as well as regarding used production system technologies. Finally, they shall reduce both the product life cycle as well as the plant life cycle. But this results in an increased production system complexity which has to be handled within the entire production system life cycle adequately.

One of the key initiatives dealing with this challenge is the German Industrie 4.0 initiative focusing on increasing flexibility of production systems and improving vertical and horizontal integration of production system components, and striving to nothing else than the 4th industrial revolution. Key elements of this initiative are (among others)

- the Industrie 4.0 component, a self-aware and self-adaptable production system component,

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- the intelligent networking of Industrie 4.0 components to provide flexibility on system level using adaptation capabilities and plug-and-work capabilities of Industrie 4.0 components, and
- the integrated exchange of Industrie 4.0 component information related to engineering and runtime phases along the production system life cycle.

Comprehensive technological developments during the last centuries are the foundation of this discussion enabling new technical possibilities within the design and use of production systems today [1]. It can be observed, that the wide-ranging capabilities of information processing systems from the consumer market has found their way into production systems realizing the vision of Computer Integrated Manufacturing (CIM) in a new fashion.

As the Industrie 4.0 component is a controlled part of a production system including manufacturing physics as well as control intelligence the Industrie 4.0 component shall be considered as a cyber physical system [2, 3] and shall be considered in the triangle of products, production processes, and resources. Each product requires for its production the processes defined in its Bill of Operation. These processes will be processed on a production resource. Each production resource will process sets of products and will be able to execute processes. Finally, each process is used for the production of products and can be executed by a resource [3]. Thus, the Industrie 4.0 component shall act as a resource providing production processes useable to produce products by exploiting its production physics and controlled by its internal control intelligence.

As proposed in [4] the life cycles of production systems and products are interlinked as presented in Fig. 1. The use of Industrie 4.0 components within these life cycles is mostly related to the plant and process development, the production system engineering, the commissioning, the use for production, the maintenance planning, and the maintenance life cycle phases (given in dark blue in Fig. 1).

Nevertheless, within these phases several engineering disciplines are involved in the development and use of the Industrie 4.0 components. Thereby, each phase consists of several engineering activities often related to necessary design decisions within one of the involved engineering disciplines. Process planning, mechanical engineering, electrical engineering, control and robot programming, and virtual commissioning are the most relevant disciplines [5]. As visualized in Fig. 2 the different engineering activities depend on each other (require engineering results of prior engineering activities) and exploit different engineering tools. In most cases, these tools are tailored to an efficient execution of the necessary work engineering activities (the optimal execution of design decisions and creation of required engineering artefacts) [6]. They are based on their own model type and their own data structure optimised to the tool use and software structure. But following the chain of engineering activities it is hard to enable a consistent and lossless exchange of engineering data (digital engineering artefacts or parts of them) between the engineering tools [7].

One mean to address the problem of consistent engineering of production systems integrating different engineering disciplines (covering the data exchange

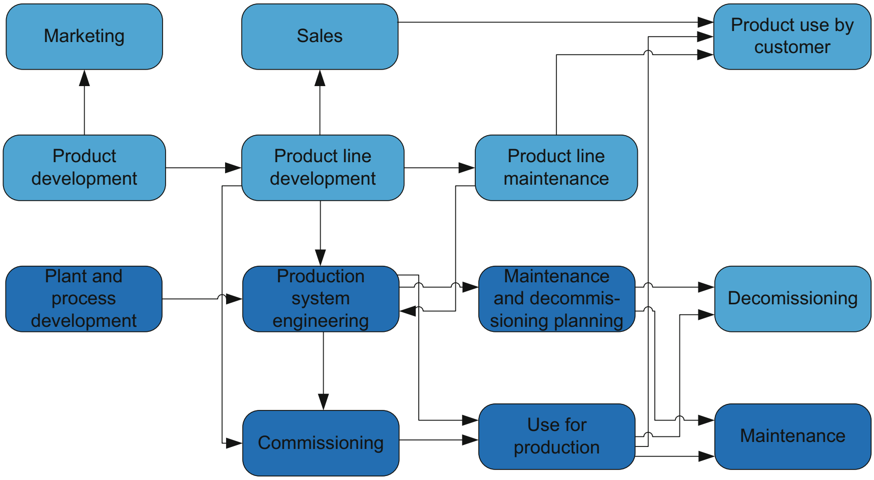

Fig. 1 Value chain oriented view on the product and production system life cycles

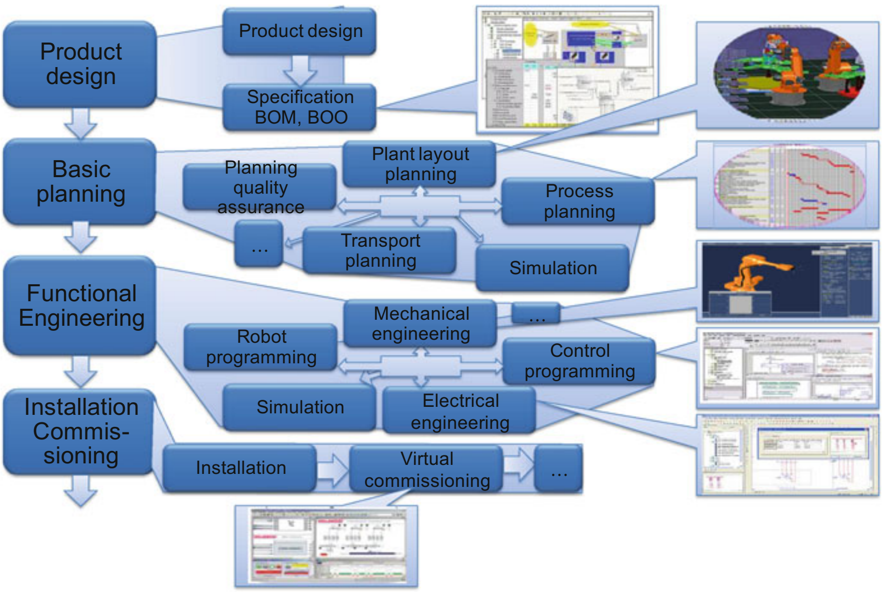

Fig. 2 Hierarchical structure of engineering process of production systems

problem, the consistency problem, etc.) is mechatronical engineering. Mechatronical thinking and mechatronical engineering, based on it, are common in product engineering and design since the seventies and the eighties of the last century.

Initially, mechatronic has been considered as supporting guideline in product design where the meaningful combination of different engineering disciplines has provided an added value for the product properties and functionalities [8, 9]. Here systems like CD players or antilock braking system have been developed. Over time, this combination had been proven useful for engineering of production systems since production systems are also product (even with the special nature of a single piece of its own) [10–12].

Mechatronical thinking within production system engineering is resulting in specific engineering processes as well as in specific production system architectures [6, 13]. Both have an essential impact on the work of engineers.

Within this paper the main concepts of mechatronical engineering within production system engineering will be considered. The terms of a mechatronical unit and a mechatronically oriented control architecture are described. Based on them the mechatronical engineering process is described as well as its main steps going beyond classical engineering approaches within machine and plant engineering. With this background the paper will analyse benefits, challenges and limitations of the mechatronical engineering process from the viewpoint of the engineering of production systems and the automation systems used within. It will draw conclusions for open research questions possibly answered by mathematical research.

2 Mechatronical Engineering

Mechatronical thinking and engineering had evolved from similar developments within the industrial countries in the late seventies and early eighties of the last century. In Germany, to give an example, the so-called "Feinwerktechnik" (precision engineering) has emerged covering the combination of mechanical and electrical engineering. The term "Mechatronic" originating from Japan has been internationally adopted for the advantageous combination of mechanical, electrical, and electronic engineering quickly. Within the following years more engineering disciplines have been integrated like optics and information sciences [14, 15].

Initially, mechatronic was focused on the design and engineering of products where the meaningful combination of different engineering disciplines can provide an additional value for the functionality, stability, etc. of intended products [8, 16]. But mechatronic has been proven to be also helpful for the structuring, design, and engineering of production systems and beyond [11, 12, 17].

2.1 Mechatronical Units and Systems in Production Systems

In recent years a broad agreement about the definition of the term Mechatronic has been established. Following this agreement it holds:

A mechatronical unit is a closed system providing a dedicated (mostly physical) behaviour within a production system utilizing sensors, actuators, and intelligent control devices in a closed loop control structure. Thereby, the mechatronical unit combines on the one hand software (for control program development) and hardware (mechanics, electrics, electronics, ...) and on the other hand different engineering disciplines to achieve an optimal functionality.

A mechatronical system is established by the systematic combination/interlinking of mechatronical units and/or mechatronical systems within a hierarchical structure. Thereby, each mechatronical system will contain its own information processing used for optimal control of the functionality and the interaction of the different interlinked mechatronical units and mechatronical systems of the lower hierarchy layers.

The distinction between mechatronical units and mechatronical systems results from the consideration of the hierarchy of mechatronical units and mechatronical systems. Usually the leaves of this hierarchy, i.e. the ends of paths, are regarded as mechatronical units while all other objects in the layers above are regarded as mechatronical systems. But most important, the mechatronical units have direct access and control of the underlying physics of the production system. It depends on the system of interest whether a drive is seen as the mechatronical unit or a power train including drive, gearbox, and frequency converter, or the complete conveyer with lifting table.

The structure and interlinking of mechatronical units and mechatronical systems covering only two layers (as simplification) is depicted in Fig. 3 to give a hierarchy example.

Following [12, 17] the complete structure of a mechatronical oriented production system can be represented by a six layer hierarchy. The lowest of these six layers is formed by mechanical and electrical parts like metal stiffeners, electrical wires, and screws. They are arranged in sub-function groups which, in combination with other sub-function groups, will provide basic functionalities of the production

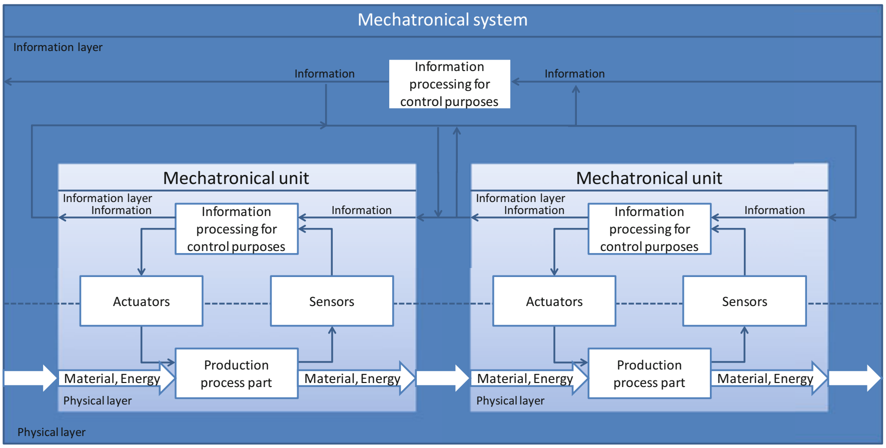

Fig. 3 Mechatronical structure consisting of two layers

system. Thus sub-function groups are grouped to function groups. For example, single clamping fixtures are combined to clamping fixture groups providing the production function "fixing material" which is required in a robot based welding cell or combining a drive, a gearbox, a frequency converter, and some shafts within a power train to provide the function "motion". Thus, function groups provide more complex functionalities which are of importance for the execution of production steps by providing essential parts of production steps. Complete production steps which are usually part of the bill of operation of a product will be provided by main groups. Main groups integrate a set of function groups as it is the case for clamping fixture groups, power trains and other function groups within a milling machine. Together, they can execute a milling function on a work piece. Main function groups can be combined to manufacturing cells able to execute sets of manufacturing steps. For example a milling machine can be combined with a robot for material handling and a storage for different milling tools in a milling cell. Finally, a set of cells can be combined to a site as a set of milling cells can be combined to an engine production site of a car manufacturer.

Usually sites, cells, main groups and function groups can be considered as mechatronical systems while cells, main groups, function groups, and sub-function groups can be regarded as mechatronical units. Here, the relevant viewpoint is essential for the definition of the lowest level of consideration which will constitute the mechatronical units. The hierarchical structure is depicted in Fig. 4.

Within the mechatronical engineering the mechatronical unit or system shall be represented by an engineering artefact covering the information sets of all relevant engineering disciplines, a kind of digital representation or digital shadow called mechatronical information object.

A mechatronical information object is an engineering artefact combining the modelling of mechatronical units of a manufacturing system with its different characteristics like signals, electrical drawings, function blocks or devices in one information object. It is the information representation of a mechatronical unit

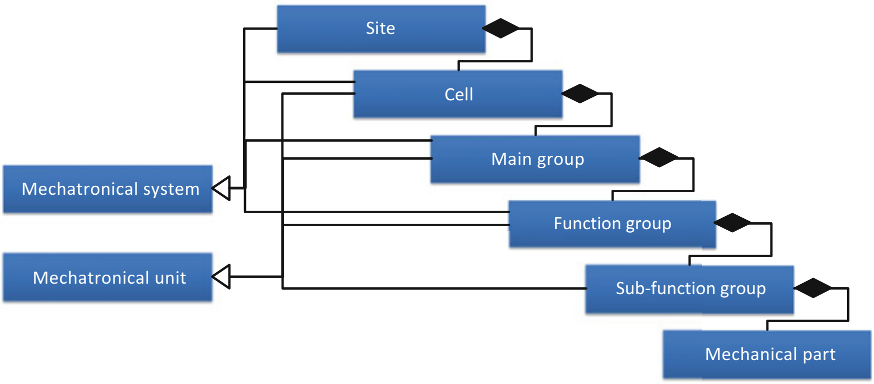

Fig. 4 Hierarchical structure of a Mechatronical oriented production system

within a mechatronical engineering process. Thus, it has to cover at least the following information sets.

- Topology data including the hierarchy of sub-elements (other mechatronical units and/or devices),
- Mechanical data including mechanical constructions with geometry and kinematics (especially mechanical drawings/MCAD),
- Electrical, pneumatic, and hydraulic data including electrical construction as wirings of the different types and their plugs,
- Function describing data like functional models of controlled and uncontrolled behaviour,
- Process control data like control code of any kind, and
- Generic data summarizing further organizational, technical, economical, and other data like order information or handbooks and guidelines.

These information sets are depicted in Fig. 5.

The relations between mechatronical engineering, mechatronical units, mechatronical systems and mechatronical information objects are given in Fig. 6.

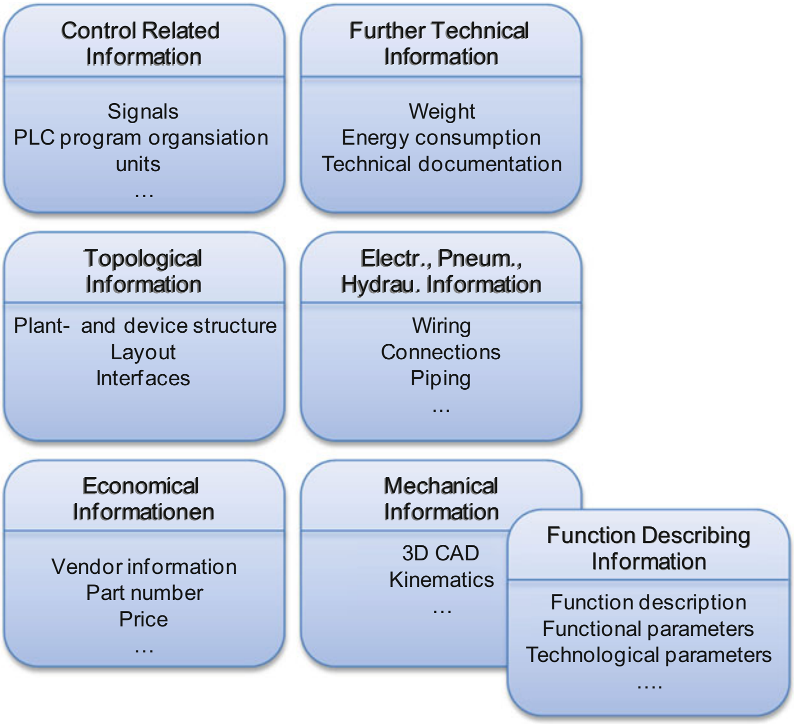

Fig. 5 Information sets of a mechatronical information object

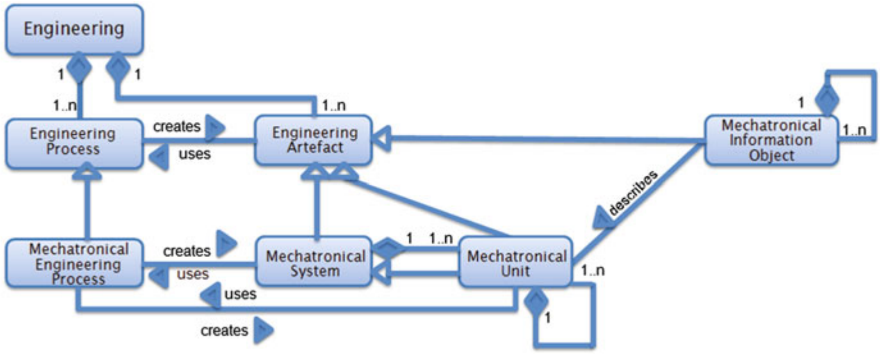

Fig. 6 Relations between mechatronic related terms defined

Within mechatronically structured production systems the control applications for production system automation are distributed among the different information processing components of the different mechatronical units and mechatronical systems. This distribution can either be a physical distribution on different control devices or a virtual distribution on the same hardware but with different execution contexts. Thereby, the control decisions executed on the different information processing units are oriented on the automation pyramid layers they belong to. Hence, on site level enterprise resource planning (ERP) decisions and control functions are executed, on cell and main function level manufacturing execution control (MES) decisions and functions are relevant, and on the different function layers field control decisions are made [18].

For the design and engineering of the automation and control applications (as well as for the complete production system design and engineering) it is useful to specify a stable interface structure for the information process units as depicted in Fig. 7 [12].

Mechatronical systems of higher layers of the production system hierarchy can access lower layered mechatronical systems using their own device interface and the execution interface of the lower layered mechatronical systems. By their execution interface lower layered mechatronical systems will provide access points to their provided production functions (or parts of it) which can be accessed by other mechatronical systems. Higher layered mechatronical systems know the required lower layered production function and can access and parameterize them appropriately by their device interface. Thus, a distributed but clear control decision hierarchy can be established.

This hierarchy is especially applied at field and MES layers of the control pyramid. Here the control application is split into components related to physical properties of production functions as depicted in Fig. 8 [19]. At the lowest level the function blocks are related to the direct physics control similar to the drivers within PC operating systems. They are responsible for operating control devices, i.e. they are relevant on the sub-function group layer of Fig. 4. Above them there

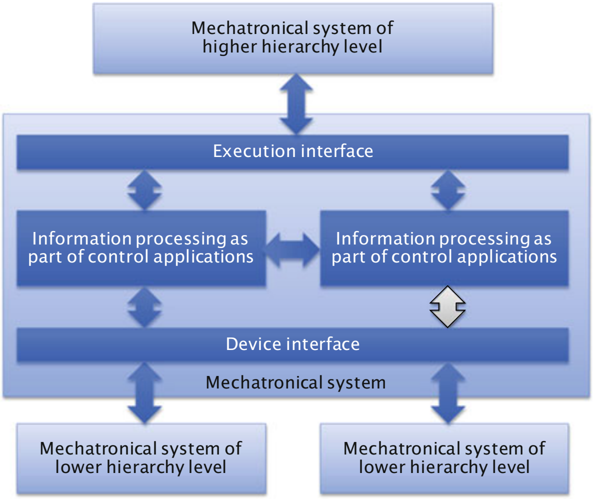

Fig. 7 Interface structure of mechatronical systems [12]

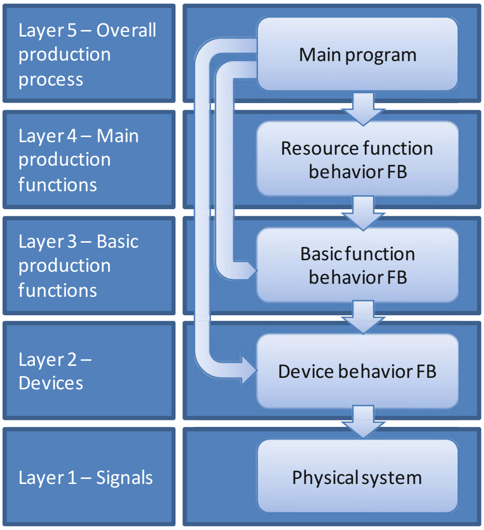

Fig. 8 Possible control hierarchy at field layer

are layers combining control devices to basic functions of the controlled system like moving a work piece until a sensor indicates its presence or move a robot into a certain pose. They belong to the function layer of Fig. 4. These function blocks are again aggregated to production system functions applicable to execute a certain production step of a product like make a welding point at position X or make a set of welding points. Thus, these function blocks belong to the main group or the cell layer of Fig. 4.

2.2 Mechatronical Engineering of Production Systems

The engineering of mechatronically structured production systems is executed with direct application of mechatronical units[1] in the structure as described above [8, 20, 21].

It can be observed, that there are two main processes to be distinguished (see Fig. 11). The first process is focused on the design, engineering, installation and commissioning of a production system intended for a special production purpose (i.e. able to produce a special product portfolio) and can be considered as project dependent engineering creating a solution for a special customer. In the course of this process mechatronical units and mechatronical systems (or parts of them) are exploited as starting points taken from a library of reusable mechatronical units.

The second engineering process serves the design, engineering, and test of reusable mechatronical units and their integration in the named library (it should be reminded that this library is not a single entity but a distributed one exploiting different storing and management technologies) and can be considered as project independent engineering creating reusable engineering artefacts independent from customer orders. These mechatronical units can be exploited within the project dependent engineering process. The design, engineering, and test of reusable mechatronical units is based on the abstraction of engineering results of the project dependent engineering process under inclusion of expert knowledge about the industrial domain the intended production systems should belong to (see [22]).

Thus, the project dependent engineering process is assigned to the engineering, implementation and use of production systems. There are structure guidelines developed for this engineering process by research projects or applied in practice (see for example [23–27]). All of them have more or less the same background of systems engineering as applied in the SysMod methodology [28]. If these processes are applied to production systems, they follow a structure presented for mechatronical engineering in [8].

This engineering process starts with the collection of requirements of the production system to be engineered. These requirements emerge on the one hand from the product portfolio to be produced, i.e. the bill of operations to be executed on the bill of material of the intended products. On the other hand there are several requirements coming from legal entities like human and environmental safety or from economical considerations (increase of earnings). Based on these requirements the overall production system is engineered in a top down decomposition approach

[1] In the following the term mechatronical unit will be used also as representative for mechatronical systems.

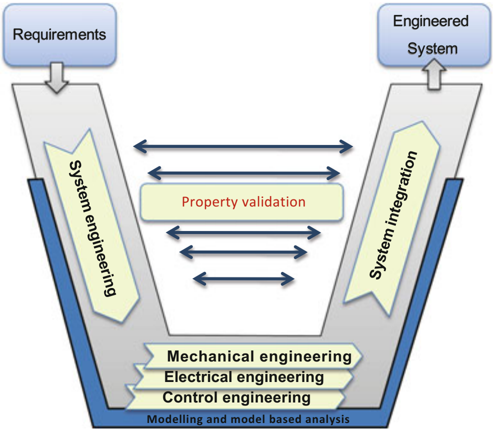

Fig. 9 Engineering process following [8]

finally resulting in a component structure to be applied in the system engineering phase. If the overall system structure is defined the different involved engineering disciplines (at least mechanical, electrical, and control engineering) have to execute the detailed engineering resulting in a detailed description of the system components. Afterwards the in detail developed system components are composed in the system integration phase and their properties are validated with respect to the initial requirements resulting in the final engineered production system. The system and detailed engineering as well as the system integration and property validation are usually accompanied by activities of modelling and model analysis to assist the engineering. This V-Model like process is depicted in Fig. 9.

Important for the mechatronical engineering of production systems are the system engineering and the system integration phases. Within these phases, at first the production function to be executed is decomposed to a function hierarchy. Therefore, the production steps to be executed are analysed and decomposed to sub-steps following the idea of main functions, functions and sub-functions executable by mechatronical units of the production system hierarchy given in Fig. 4. If necessary the identified production process related functions are assisted by auxiliary functions required to enable the production functions. In each decomposition step it is analysed if there are possible realisations of the functions of interest within the mechatronical library, i.e. are there solution elements for the required functions. If so these solution elements are assigned to the functions. Thereby, in parallel to the function hierarchy also a solution structures is developed [29, 30].

An example of this decomposition is given in Fig. 10. Here a welding cell for car body manufacturing is considered. This welding cell is dedicated to execute a set of spot welding steps following the assembly sequence of the car body. Thus, for welding the welding function is required but also clamping functions and transportation functions within the welding cell. To have the material to be welded in the welding cell it has to be inserted into the cell in an insertion area and to be transported to the insertion area. All these necessary functions are given by

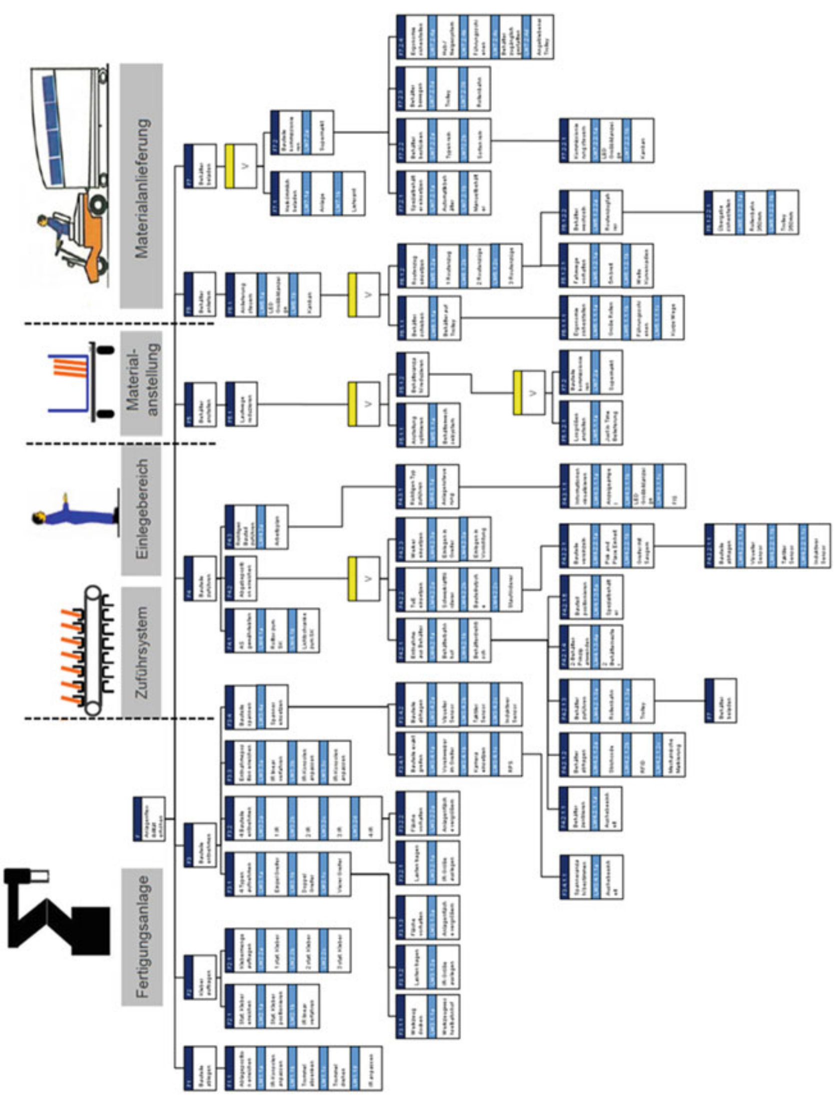

Fig. 10 Example of a function hierarchy with assigned possible solution elements

dark blue boxes in Fig. 10. For each function applicable technical realizations are available given in light blue in Fig. 10. For example the welding can be executed by a welding gun either mounted on an industrial robot or on a static welding station. In case of a robot mounted gun the material has to be fixed on a geo station while in case of a static welding station the material shall be clamped and moved by a robot to and within the welding station. There are several human based or human free realization possibilities for material insertion and material provision as well.

The system integration phase can start if at least one possible solution element is identified for all leaves of the function hierarchy by either selecting it from the mechatronical library or by developing it from scratch within the detailed engineering. Then, the different system components are combined, connected, validated, implemented, and commissioned.

As named above, within this activity mechatronical units are used as input from a mechatronical library. On the one hand they are an input to the system function decomposition and solution element identification. In addition, they are applied and sometimes adapted in the detailed engineering, implementation, and commissioning of the production system providing necessary engineering artefacts for these phases.

If a project dependent engineering process for a production system is finalized the engineering results can be considered for identification of reusable system elements (i.e. mechatronical units). The system elements of the developed system are evaluated against customer and market requirements as well as technological progress expectations. Thereby, mechatronical units are identified, separated, completely engineered, possibly realized and tested, and finally added to the mechatronical unit library (Fig. 11).

As an example for this process the engineering of the control architecture within a production system shall be considered in detail.

Within the system engineering phase a hierarchy of mechatronical units is identified realizing the necessary production process. Following the control architecture of a mechatronical unit depicted in Fig. 7, the interaction of mechatronical units depicted in Fig. 3, and the hierarchy of mechatronical units given in Fig. 8, to each

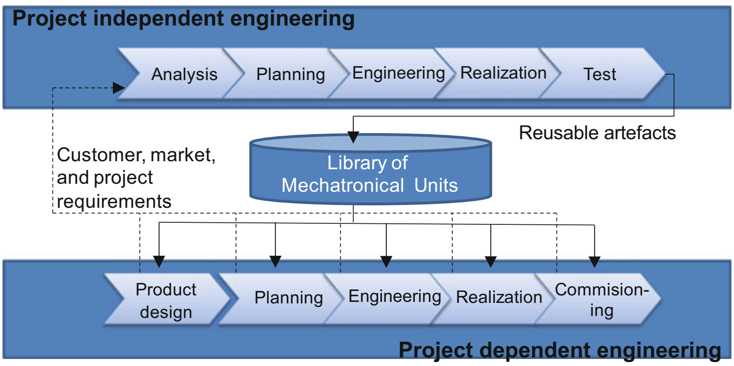

Fig. 11 Two processes within mechatronical engineering following [20]

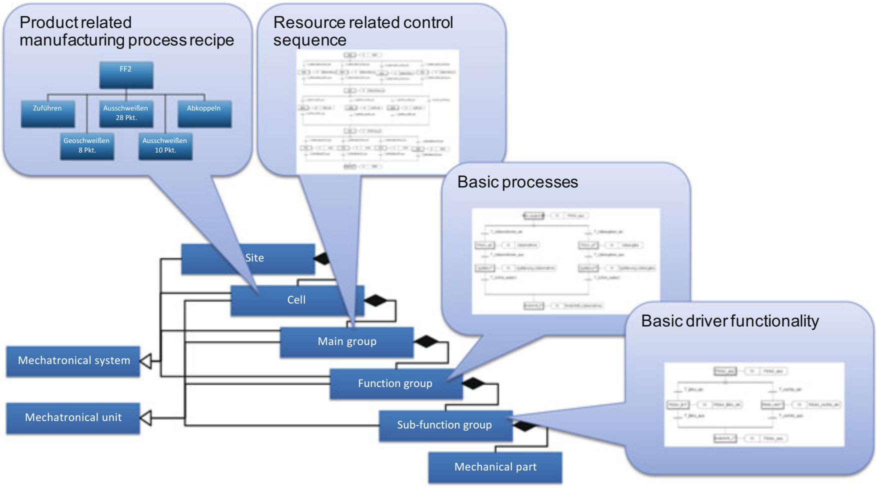

Fig. 12 Hierarchy of control application

of the layers of the identified hierarchy of mechatronical units a dedicated control application is assigned to.

At the cell layer this part represents the sequence of production process steps to be established in the cell. In the welding cell example these are the material transport and the welding steps. The cell layer exploits the resource related control sequences of the different main groups (e.g. robots, conveyers, etc.) creating the necessary sequences of the main groups (e.g. move robot to a position, transport material to a position, close clamping fixture). The main groups exploit the function groups and their control in the same way and finally the function groups exploit the sub-function groups representing the lowest layer of control accessing the sensor and actuator devices of the production system (e.g. start motion of a drive, read state of inductive proximity switch). This control code hierarchy is depicted in Fig. 12.

Having the necessary mechatronical units with their control code for the defined control applications within the mechatronic library the control code design step within the detailed engineering as well as the validation of the integrated system behaviour becomes easier. Here model based engineering actions as described in [26, 31–33] (for control engineering) and [34–36] (for control system validation) can be applied to name only some examples.

Based on several successful engineering processes the provider of production system components of the different layers of the mechatronical hierarchy can identify design pattern for component control. Usually, similar applications are grouped to classes of application as identified for drive applications in [37, 38]. The 12 identified application types are presented in Fig. 13.

Fig. 13 Different application types as identified by Lenze [38]

3 Existing Benefits of Mechatronical Engineering

A first benefit of the mechatronical engineering is obvious, the reuse of existing engineering artefacts as envisioned by [22] or [24]. After executing a project dependent engineering process appropriate project parts and/or system components can be identified and treated for reuse and integrated in the library of mechatronical units/systems in a project independent engineering process. Within the next project dependent engineering process requiring similar solutions these mechatronical units can be applied. Thereby, engineering effort in detailed engineering, validation, installation, and commissioning can be reduced providing a shorter engineering process with better tested components and less errors, and, finally, a better project quality.

The second benefit is related to the problem of cooperation of several engineering disciplines within the engineering process. As envisioned in VDI 3695 [20] a common architecture for the work of the different engineers involved in an engineering process is improving the process quality and efficiency. It will provide a kind of a common dictionary containing common system element types (with different discipline dependent views), a common system structure (plant hierarchy), and, finally, the ability of identification of common object entities in the different disciplines.

Beyond the common vocabulary avoiding misunderstandings between the involved engineers the data management within the engineering process can be improved drastically. Mechatronical engineering can be exploited related to data base based data exchange within the engineering process with common object semantics as discussed in [39] and related to exchange data format based engineering chain setup as discussed in [6]. This will result in improved tool chains (all disciplines crossing data exchange) providing the ability of lossless and consistent data exchange among involved engineering tools.

The fourth benefit is less visible as it is not related to engineering artefacts of the engineering chain. Within the system engineering phase the production system is initially considered from a function oriented point of view independent from the different possible technical realisations of the production system. The function hierarchy is developed. To each relevant function the set of possible realisations is assigned. Using this assignment, theoretically, the complete set of possible plant structures can be developed and the optimal one is selected. Despite the fact, that this optimization problem is not solvable realistically, it is possible to identify a set of meaningful candidates for final realization and discuss benefits and drawbacks of the realizations based on a more abstract level. This approach has been successfully applied within graduation activities of the research institute of the authors in the fields of welding cells in car body manufacturing, cutter systems in roller mills, stone mills, punching systems for metal sheet processing and robot gripper design to name only some examples.

4 Existing Challenges

To realise the named benefits mechatronical engineering provides some challenges to be solved to enable the successful application of this engineering methodology.

At the beginning of the engineering process (within the system engineering phase) appropriate mechatronical units/ systems have to be identified applicable as technical realisation of required functions of the production system. In the case of a body welding shop for car manufacturing for example, the engineering process is given as a set welding points to be made on special steel geometries to weld them together. Here libraries of mechatronical units can assist engineers by providing best practice system components. In the welding case the welding point structure and the steel part geometry for example can call for a special welding gun which will be provided as mechatronical unit or a complete welding robot consisting of a 6-axis robot with welding gun and cable-hose assembly. But these mechatronical units have to be modelled appropriately and should be automatically selectable based on relevant differentiating factors (in the car welding case for example the welding current and the gun size). The selection process requires a comparison of the required function and the functional capabilities of the mechatronical unit/system (like welding with welding parameters like temperature and material types). In addition, the general conditions of the usability of the mechatronical unit have to be evaluated. It is an ongoing discussion how the required and provided capabilities of mechatronical units can be modelled. There are first existing ideas based on the generic description of manufacturing functions as described in [29, 40–42].

Theoretically, if a set of possible mechatronical units has been selected for the different elements of the function hierarchy the optimal set of mechatronical units/systems can be calculated. The optimization methodologies required for this problem could be a kind of a linear program integrating the capabilities of the mechatronical units, their mutual exclusion and dependencies, and the economical effect the application can have (costs, throughput, etc.). Similar ideas for a manufacturing process flexibility based optimization in the field of scheduling have been presented in [43]. It needs to be regarded that this optimization problem may suffer from the theoretical size of a production system and its hierarchies. In [44] a nine layer hierarchy of production system components has been proposed applicable for the modelling of a production system in the automotive industry. On each of these layers mechatronical units can be found leading to a capability of reusing mechatronical units on these layers. Up to now there is no stringent mathematical modelling available covering this optimization problem (Fig. 14).

Having a system structure defined, the involved engineers of the different engineering disciplines (including the control engineer) have to execute a detailed engineering providing the detailed description of the production system to be built. During the process flow of the engineering the made descriptions get more and more detailed exploiting different types of descriptions ranging from high level/abstract models over more detailed models down to implementable code and detailed drawings. In the case of a welding shop for car body manufacturing the set

	Layer	Example	
9	Production network	VW cooperation	
8	Factory	Golf 7 production system	
7	Production Line	body shop line	
6	Production Line Segment	vehicle body line	
5	Work Unit	vehicle body plant	
4	Work Station	welding cell	
3	Function Group	welding group (robot, controls, welding equipment)	
2	Component	welding gun	
1	Construction Element	welding cap	

Fig. 14 Production system hierarchy following [44]

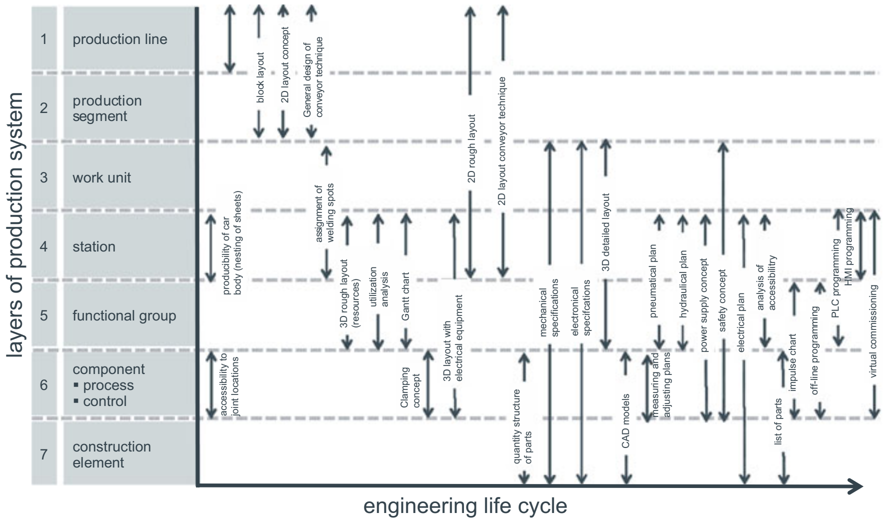

Fig. 15 Engineering artefacts required within welding shop engineering for automotive industry (selection)

of engineering artefacts is larger than 30. Figure 15 gives an overview how they are assigned to production system layers.

All created artefacts (models, drawings, etc.) represent the same system and shall be consistent to each other crossing engineering disciplines and levels of detail. For example, the mechanical, electrical, pneumatical and hydraulical models need to be in line with the 3D layouts and the part lists. In addition some of its characteristic properties will depend on each other. If, for example, a drive defined in the mechanical engineering has a special electrical interface this interface need to be connected in the electrical engineering were the connections enable the necessary ampere and volt of the energy flow to the drive. An example of first approaches addressing this problem is given in [39].

Needless to repeat, the availability of models within the engineering process opens up the complete box of the Pandora for model driven engineering. A survey of model driven engineering for distributed control systems is given in [45] as an example.

If the overall system is engineered in detail the correctness of the engineering can be validated based on virtual commissioning approaches. Therefore, the different models of different engineering disciplines need to be combined and a joint system simulation has to be executed [46]. Thereby, an adequate combination of models of production system physics and production system control at different layers are required. To come back to the welding shop example the physical stability of steel parts and its twist based on gravity forces within the material holders may have an effect on the necessary positions of material fixtures as well as the positioning of the welding gun. This information is only available if material physics is also considered in the simulation model. As the different modelled objects are of different nature (continuous vs. discrete event, abstract vs. detailed, physical vs. logical, etc.) the models to be combined are very heterogeneous and their simulation requires various simulation strategies and tools.

5 Open Research Questions

Looking on the challenges of mechatronical engineering (which are far not new) still a set of open issues for mathematical research can be identified improving the applicability of mechatronical engineering.

As the engineering of production systems gets more and more model driven, there is an increasing need for methodologies following the model driven thinking. Models have to be created, processed, applied for generation of other (often more detailed) models or other descriptions and finally be executed (for example in controllers). In addition these models follow a multi-model approach with different usually overlapping models of the different involved engineering disciplines.

Research Question 1 Mathematical research can assist production system engineering by improving the capabilities for model generation, model transformation, model integration and model consistency management. Especially the crossover between models of different model nature (discrete event, continuous, hybrid ...) as well as models of different disciplines is of interest which has to be based on a common meta modelling approach for production systems.

One essential part in mechatronical engineering of production system is the automatic selection of potentially mechatronical units implementing special production system functions. Therefore, models of manufacturing functions are required applicable for automatic comparison of provided and requested functions. First approaches like [47–51] need to be extended and enriched with respect to expressiveness to be applicable in optimization methods.

Research Question 2 Mathematical research can assist production system engineering by enhancing production function models towards applicability in comparison and optimization methodologies.

At the end of the engineering of production systems more and more virtual commissioning methodologies are applied enabling a validation/verification of production system properties. Therefore, the created system of engineering artefacts (models) need to be combined appropriately and executed in simulation systems. Currently the simulation is only possible for limited sets of models over limited model sizes.

Research Question 3 Mathematical research can assist production system engineering by enhancing model combination and model simulation/co-simulation strategies improving the applicability of virtual commissioning to larger and more complex systems.

Facing the named challenges can be a task for a joined effort of mathematical and engineering science research. This paper will explicitly appeal interested researchers to cooperate under the roof of the Industrie 4.0 approach.

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