INTERNATIONAL DESIGN CONFERENCE - DESIGN 2010
Dubrovnik - Croatia, May 17 - 20, 2010.

DESIGN 2010

A SPECIFICATION TECHNIQUE FOR THE INTEGRATIVE CONCEPTUAL DESIGN OF MECHATRONIC PRODUCTS AND PRODUCTION SYSTEMS

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Keywords: conceptual design, mechatronics, principle solution, process planning, production system development, specification technique

1. Introduction

The prevailing market and competitive situation requires companies to develop and produce their products fast and cost-effective. Often the used manufacturing technologies highly determine the product concept. Against this background product and production system have to be developed in an interplay from the beginning. This is in particular necessary for complex products. For example for mechatronic products, which can be distinguished as an integration of mechanics and electronics in a confined space. Today the dependencies between product and production system are not considered adequately. The results are time-consuming and cost intensive iteration loops during the development process.

The present paper focuses on a specification technique for the description of the principle solution of a production system based on the principle solution of the product. The development of the production system starts at an early stage of the product development process, namely if first relevant information for production is available. From this point on product and production system are developed in a close interplay and in parallel because of their detected interactions. The principle solutions of the product and the production system are fundamental to the communication and cooperation of the participating specialists in the course of production system development.

The concept is based on investigations of the cooperative project VireS "Virtuelle Synchronisation von Produktentwicklung und Produktionssystementwicklung". The outcome of this project is a methodology for the integrative development of product and production system at an early design stage. It considers the aspects manufacturing costs and robustness against market driven change requests. The methodology consists of a process model, a specification technique and tools for the evaluation of costs and robustness. It is validated in four ambitious industrial projects.

2. Problem Analysis

The product development process ranges from the product idea or business idea to a successful market entry and covers the activities strategic product planning, product development and production system development [Gausemeier et al. 2009b]. In our experience the product development process cannot be seen as a stringent sequence of process steps. It is more an interplay of tasks that can be structured into three cycles (figure 1).

The first cycle: Strategic Product Planning

This cycle characterizes the steps from finding the success potentials of the future to create the promising product design, what we call the principle solution. There are the four major tasks foresight, product discovering, business planning and conceptual design in this cycle.
The second cycle: Product Development
This cycle covers the three phases domain-spanning conceptual design, domain-specific concretization and system integration. Within the last phase the domain-specific results are integrated into one overall solution. In this context the creation and analysis of computer models are an important part, which leads to the widely used term Virtual Product and Virtual Prototyping respectively.
The third cycle: Production System Development

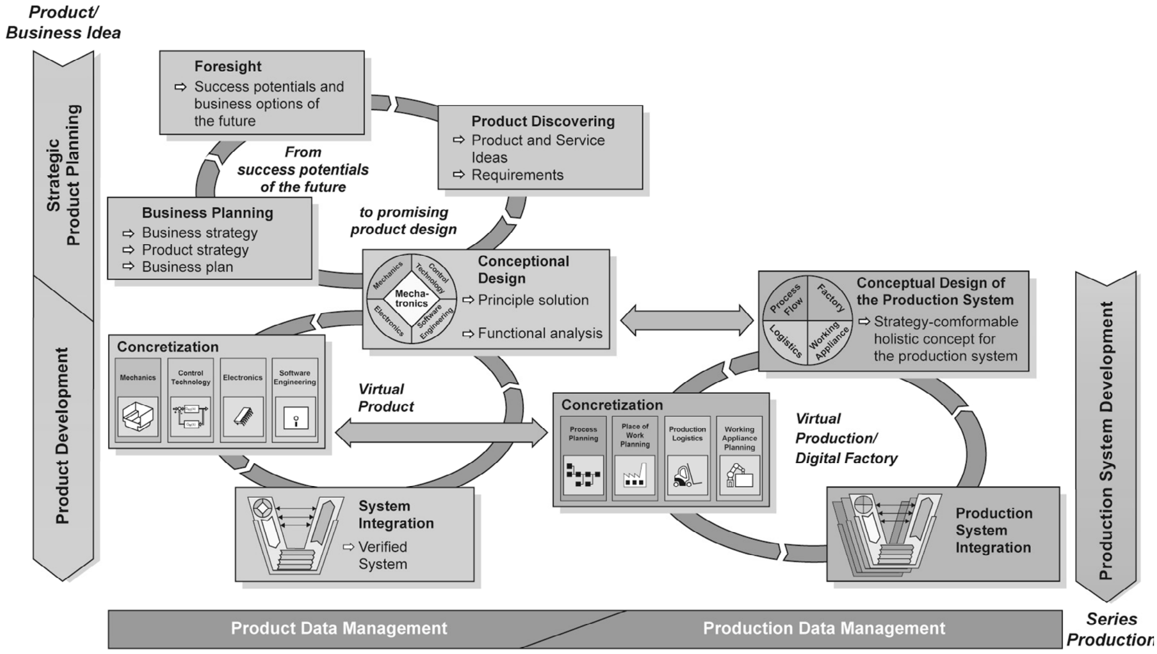

Figure 1. 3-cycle-model of product design according to GAUSEMEIER

The starting point of this cycle is the conceptual design of the production system. The result of this phase is the principle solution of the production system. In the further course of the third cycle the four main aspects process planning, place of work planning, production logistics and working appliance planning have to be concretized further. In this process partial models occur, which have to be integrated to a coherent system of partial models.
The product and the production system have to be developed in a close interplay. This is in particular necessary for complex products, whose concept is affected by the considered manufacturing technology. Because of this, the product development and the production system development are arranged in parallel. The horizontal arrows in the model of three cycles emphasize, that the conceptual design of product and production system has to be dealt in a closely interplay. In this context, the principle solution of the product constitutes the starting point for the production system´s conceptual design.
At the Heinz Nixdorf Institute a specification technique for the domain-spanning description of the principle solution of mechatronic systems has been developed [Gausemeier et al. 2009a]. The principle solution of a highly complex system needs to be divided into aspects. According to Figure 2, those aspects are: environment, application scenarios, requirements, system of objectives, functions, active structure, shape and behavior. The mentioned aspects are mapped on computer by partial models. Because the aspects are in relationship with each other and ought to form a coherent system, the principle solution consists of a coherent system of partial models. It is necessary to work alternately on the aspects and the according partial models, although there is a certain order [Gausemeier et al. 2009a].

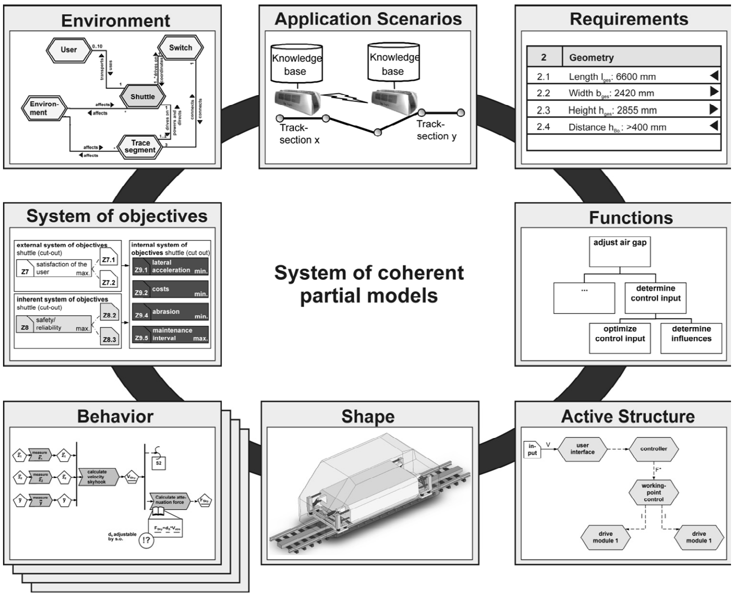

Figure 2. Partial models for the domain-spanning description of the principle solution of mechatronic systems

The description of the environment, the application scenarios and requirements serve as the starting point. They are usually followed by the system of objectives (in case of self-optimizing systems), the function hierarchy and the active structure. The active structure represents the core of the principle solution in conventional mechanical engineering. The mentioned partial models are described below. For a detailed description we refer to [Gausemeier et al. 2009a].

Environment: This model describes the environment of the system that has to be developed and its embedding into the environment. Relevant spheres of influence (such as weather, mechanical load, superior systems) and influences (such as thermal radiation, wind energy, information) will be identified. Disturbing influences on the purpose of the system purpose will be marked as disturbance variables. Furthermore, the interplays between the influences will be examined. We consider a situation to be one consistent amount of collectively occurring influences, in which the system has to work properly. We mark influences that cause a state transition of the system as events. Catalogues, that imply spheres of influences and influences, support the creation of environment models.

Application scenarios: Application scenarios form first concretizations of the system. They concretize the behavior of the system in a special state and a special situation and furthermore, what kinds of events initiate a certain state transition. Application scenarios characterize a problem, which needs to be solved in special cases, and also roughly describe the possible solution.

Requirements: This aspect considers the computer-internal representation of the requirements. The list of requirements sets up its basis. It presents an organized collection of requirements that need to be fulfilled during the product development (such as overall size, performance data). We distinguish between functional and non-functional requirements. Functional requirements describe the desired functionality of the system. Non-functional requirements describe properties of the system itself as well as of its behavior. Every requirement is textually described and, if possible, concretized by attributes and their characteristics. There are checklists that assist the setting up of requirements, see for example [Pahl et al. 2007], [Roth 2000].

System of objectives: Objectives in terms of self-optimization describe the behavior of the system to be achieved. The objectives are realized by the system itself during its operation. The objectives of a self-optimizing system build together a system of objectives. Further information regarding the system of objective and self-optimization can be found in [Gausemeier et al. 2009a].

Functions: This aspect concerns the hierarchical subdivision of the functionality. A function is the general and required coherence between input and output parameters, aiming at fulfilling a task. For the setting up of function hierarchies, there is a catalogue with functions which is based on [Langlotz

2000]. Functions are realized by solution patterns and their concretizations. A subdivision into sub functions is taking place until useful solution patterns have been found for the functions.

Active structure: The active structure describes the system elements, their attributes as well as the relation of the system elements. The active structure consists of system elements, such as drive and break modules, air gap adjustment, operating point control, tracking modules, spring- and tilt modules, energy management and their relations. Furthermore, incoming parameters are described, such as comfort, costs and time, which are external objectives of the user.

Shape: This aspect needs to be modeled because first definitions of the shape of the system have to be carried out already in the phase of the conceptual design. This especially concerns working surfaces, working places, surfaces and frames. The computer-aided modeling takes place by using 3D CAD systems.

Behavior: Two partial models are used to specify the behavior of the system. These are the partial models behavior – states and behavior – activities. The partial model behavior – states defines the states of the system and the state transitions. The state transitions describe the reactive behavior of the system towards incoming events. The partial model behavior – activities describes the logical sequence of activities in the system. Especially, parallel executed activities and their synchronization can be described this way.

The starting point for the development of the production system is the principle solution and not the completely defined product because the development of the production system must be done concurrently to the development of the product. The conceptual design of the production system starts as soon as first relevant information for production is available. The product´s principle solution allocates this initial information. Particularly the aspects requirements, active structure and shape are relevant for the conceptual design of the production system.

The four main aspects of the production system development, process planning, place of work planning, production logistics and working appliance planning base on a completely defined product.

There is a gap between the abstract principle solution of the product and the concretization of the production system within the four main aspects by well-established specification techniques. For this reason a specification technique for the description of the principle solution of production systems at an early stage of the product development process is required. The specification of the principle solution sets up the basis to the concretization of the four main aspects. Furthermore the principle solution represents the basis for all the experts´communication and cooperation in the curse of the further concretization. Figure 3 illustrates this circumstance.

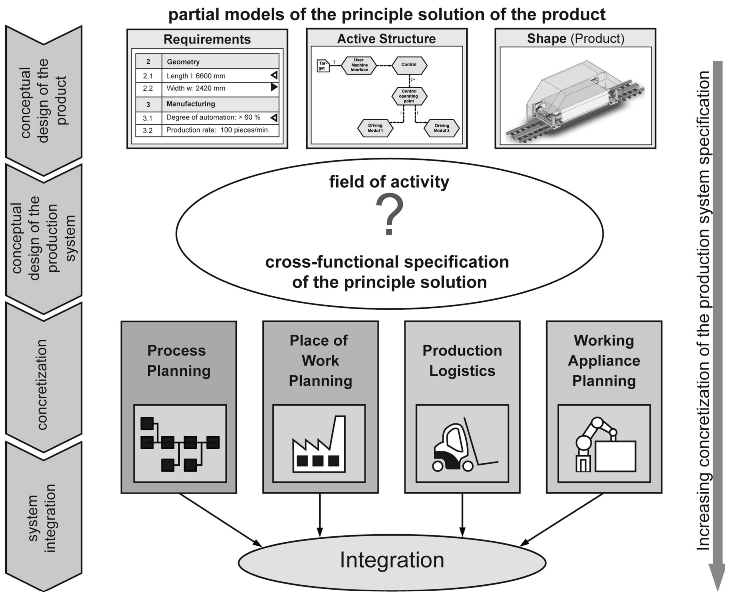

Figure 3. Central challenge: a new specification technique for the description of the principle solution of production systems based on the principle solution of the product

Today, existing approaches do not provide an integrative conceptual design of product and production system at an early stage of the product development process. Some approaches support the reorganisation of existing manufacturing systems by providing a range of optimisation strategies [Zaeh et al. 2005]. Others focus on the creation and evaluation of technology chains [Brecher et al. 2005] or provide product-process or even product-process-resource models in combination with methods to use them [Feldmann et al. 2008]. All of the above focus on the production system planning. As a rule, the starting points are ready developed products. Furthermore the particularities of the domain-spanning development of mechatronic systems are not considered.

3. Demonstrator – Miniature Robot BeBot

The miniature robot BeBot (figure 4), developed at the Heinz Nixdorf Institute, is used as a demonstrator to present and validate the developed specification technique. It serves as a test carrier for swarm intelligence, for multi-agent applications of the computer science and for the use of new manufacturing technologies.

The robot is characterized by a close spatial integration of mechanics and electronics based on the technology Molded Interconnect Devices (MID). The exterior is realized as a MID-component. It comprises mechanical and electrical components. The conductors, between the more than 100 component parts, cover the interior of the robot’s chassis and create a complex, a three-dimensional circuit – everything resulting in a high density of functions and a support for the miniaturization. In this way the amount of component parts is enormously small – in comparison with conventional robots.

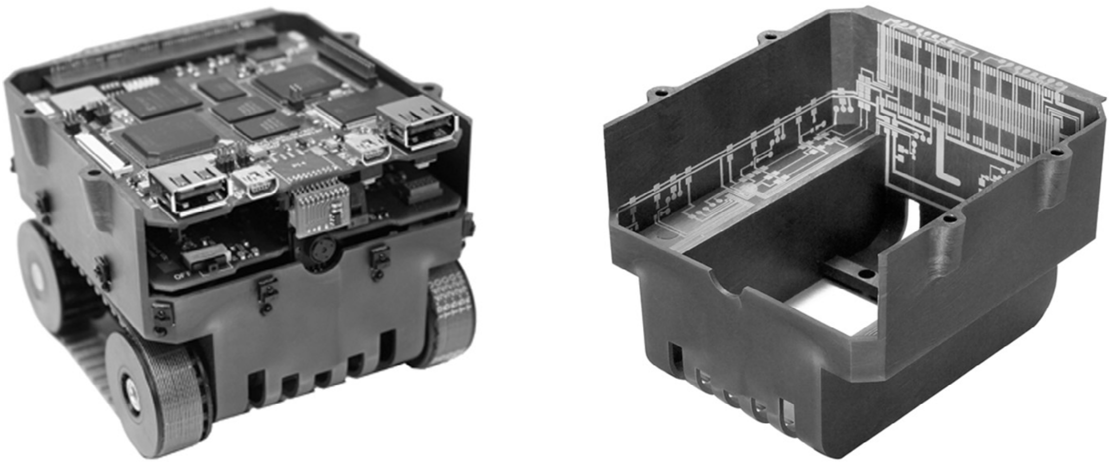

Figure 4. Basis module of the miniature robot BeBot (left figure) and its housing with integrated circuit traces (MID) (right figure)

4. Specification Technique for the Description of the Principle Solution of Production Systems

In the following, we present a specification technique for the description of the principle solution of production systems, based on the principle solution of the product. Already at the beginning of the work, it became clear that a comprehensive description of the principle solution of production systems needs to be devided into aspects (cf. [Michels 2006]). These aspects are: requirements of the production system, process sequence, resources and shape of the production system [Brandis et al. 2009]. As well as the product´s aspects, they are mapped on computer by partial models. These partial models have to be integrated. Therefore the principle solution consists, analog to the product´s one, of a coherent system of partial models.

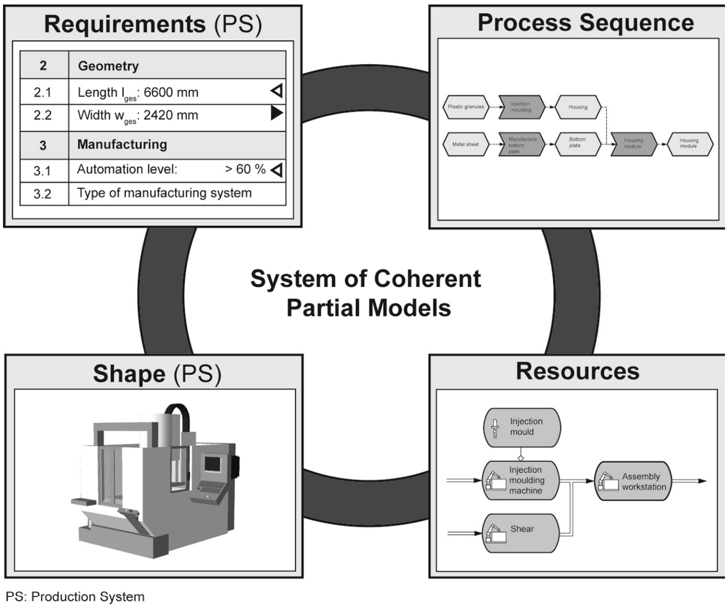

Figure 5. Aspects for the cross-functional description of the principle solution of production systems

The processing of these aspects and their corresponding partial models is done in an interplay, although a certain sequence exists. Figure 6 illustrates the principle process of the conceptual design of production systems by means of the partial models and their interrelationship.

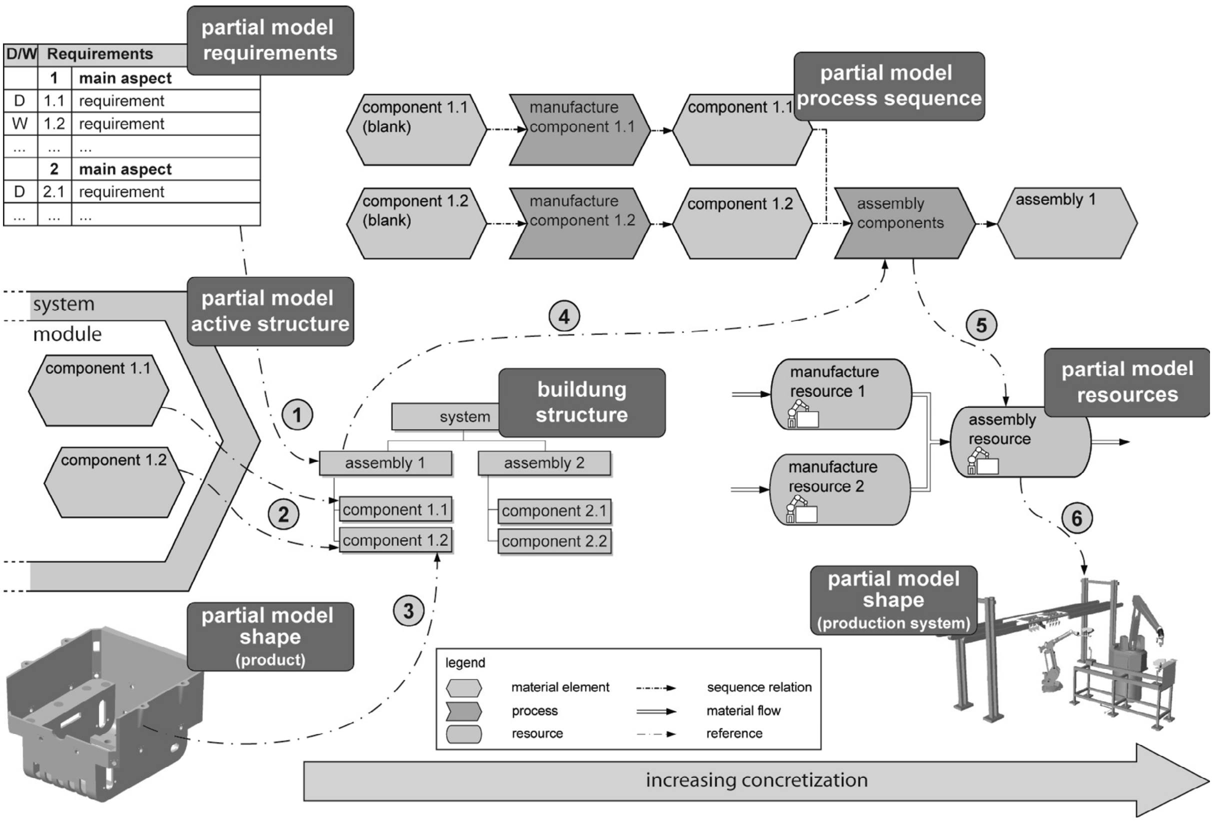

Figure 6. Principle approach of the conceptual design of production systems

Based on the principle solution of the product, the conceptual design of the production system starts. Particularly the three aspects requirements, active structure and shape of the product´s principle solution contain the relevant information (cf. figure 2). These three aspects mark the starting point. In addition to the product requirements the partial model **requirements** provides production system related requirements. Requirements relevant to the production system are filtered out. For example possible materials or degree of automation. The **active structure** and the **shape** describe the components which need to be manufactured and their spatial relations.

Based on the information from the requirements (1), the active structure (2) and the product shape (3) a first **building structure** is developed. The building structure describes the spatial and logical aggregation of components to assemblies and products [Pahl et al. 2007]. Based on the functional and spatial correlations of the active structure and the shape and if nessesary further partial models, the components and assemblies are structured under manufacture and assembly aspects [Steffen 2007]. In this case, the building structure shows that the component 1.1 and 1.2 are assembled to a subassembly. The two subassemblies assembly 1 and assembly 2 form the complete system.

The information contained in the building structure is used to establish a first assembly and manufacturing sequence (4). The processes as well as the product components are depicted on the partial model **process sequence**. The process sequence is the core of the principle solution of the production system. Each process is described by a manufacturing function. Those manufacturing functions are concretized to manufacturing processes and technologies. Thereby the interactions between the applied technologies need to be considered and alternative technology chains need to be evaluated. For that approved methods are used, e. g. the methodology for evaluating manufacturing sequences by [Brecher et al. 2005].

Next, **resources** are allocated to the several processes (5). Resources are needed to realize the chosen manufacturing technologies (cf. [Cisek et al. 2002], [Zaeh et al. 2005]). In this case, an assembly resource is assigned to the assembly process.

In contrast to the processes, resources have a **shape** (6). The partial model of the same name contains this information, e.g. the workspace or the required floor. The four mentioned partial models as a whole describe the principle solution of the production system. In the following, a detailed description of these partial models is given.

4.1 Requirements

Analog to the principle solution of the product, this aspect considers the computer-internal representation of production systems´ requirements. It presents an organized collection of requirements posed to the production system. The basis provide the requirements stated in the principle solution of the product. Shape related requirements (e.g. material, tolerances, surface finish etc.) as well as production related requirements (e.g. production volume, costs, deadlines) are of particular interest. They are used to derive requirements on the applied manufacturing equipment (e.g. the dimensions of the working spaces, speed of operation). The requirements are verbally described and concretized by attributes and their characteristics. There is a distinction between demands and wishes (c.f. [Pahl et al. 2007]).

4.2 Process sequence

This partial model describes the manufacturing operations (activities) and their sequence as a chain of processes. We refer to the processes as manufacturing processes and assembly processes. Each process is characterized by a manufacturing function and additional attributes (requirements, process parameter). According to product functions, manufacturing functions are described by a substantive and a verb (e.g. machining the housing, assemble wheels). During the conceptual design the manufacturing functions are concretized into manufacturing processes and manufacturing technologies. As manufacturing processes we consider predominantly manufacturing processes according to the standard DIN 8580 [DIN8580 1974]. Each process has at least one input-object and at least one output-object. The input and output objects are referred to as material elements. That includes all raw materials, auxiliary materials, components from suppliers and trade goods, as well as raw, unfinished and finished goods [Gienke et al. 2006]. Such as processes, material elements are detailed by further information, requirements and shape. Manufacturing processes carry out a transformation of components and assemblies with regard to form and material properties. To increase the clearness of the process sequence, it is possible to mask out the output objects of processes in which no transformation of the material element's form or properties occurs, for example positioning operation.

Figure 7 illustrates a detail of the process sequence of the miniature robot´s housing with drive mechanics. The module consists of MID-housing, electric motor, wheels and chains. The manufacturing of the MID-housing is shown in the upper sequence. The initial process is the master forming of the housing by injection moulding. Thereby plastic granules are transformed into an unprocessed housing. The process injection moulding is characterized by requirements and process parameters. Examples for requirements are allowed materials, draft angle and maximum thickness. Pressure, moulding holding time and cooling time are only some of the examples of process parameters. The final machining closes the manufacturing, the result is the finished MID-housing. Requirements and shape of the MID-housing are specified. The usage of liquid crystal vectra is demanded, a dark color is wished. The shape is stored as written specifications, e.g. dimensions and tolerances. The lower sequence shows the manufacturing of the drive wheel. This process is very abstract because the available information is incomplete. Only input and output objects are known. The assembly is carried out in three steps. First the wheel and the bearing are assembled. The result is the drive wheel. Second the electric motor is mounted into the MID-housing. Those two assembly processes are independent from each other. The final process is the assembly of the completed housing, including the electric motor, carrying and drive wheels and track chains as input. The produced output is the housing with drive mechanics.

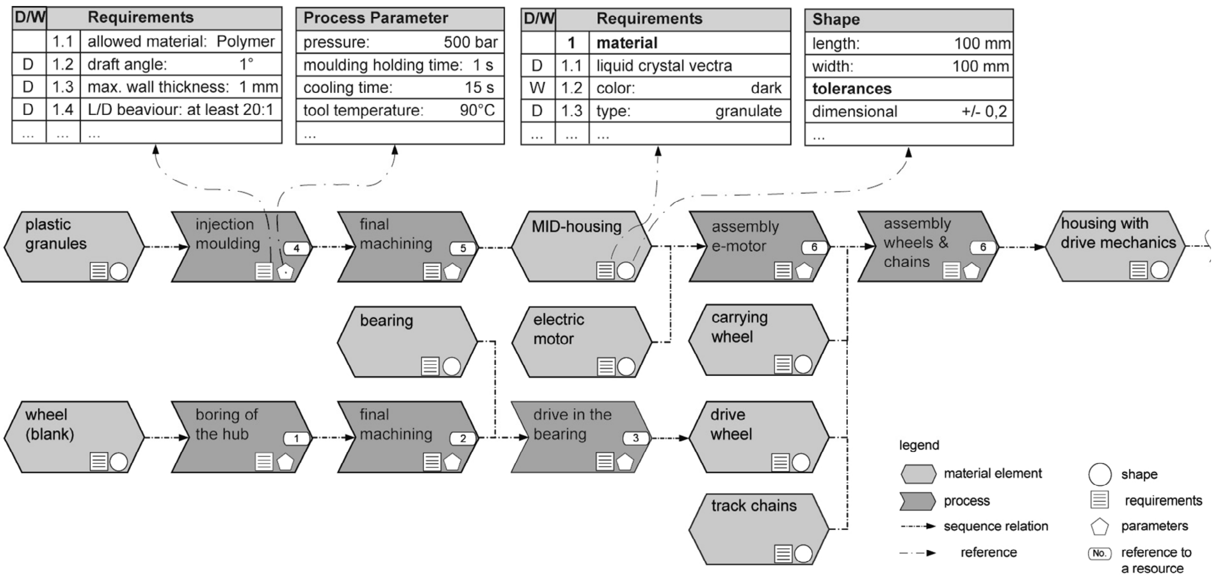

Figure 7. Process sequence of the miniature robot BeBot (detail)

4.3 Resources

This partial model describes the resources that execute the processes within the process sequence partial model. We refer to the resource as all equipment, tools and personnel that are required for the execution of processes [DIN69902 1987]. The resources are allocated to the processes of the process sequence. It is possible that one resource realizes more than one process. The resources are connected by arrows indicating the material flow. It is derived from the process sequence. Resources are concretized by requirements, parameters and shape.

The resources related to the process sequence of the miniature robot (figure 7) are illustrated in figure 8. The manufacturing of the housing is shown in the upper sequence. The initial resource is the injection moulding machine. It executes the process injection moulding. The required production rate is 12 pieces per hour. The resources parameters presents a range of parameters and values that the resource is capable to perform. In this example details about pressures are particularly important, for example the possible boost is between 500 and 1500 psi. The injection moulding machine requires an area of 2000 x 5000 mm with a maximum height of 2600 mm. The three resources in the lower sequence represent the manufacturing of the drive wheel. In the course of the concretization, the resources are detailed by further resources, e.g. machines by tools. In figure 8 the CNC lathe is detailed by an associated tool – the lathe tool. This is done because information about the used lathe tool is of prime importance for the interaction between product and production system.

4.4 Shape

Analog to the conceptional design of the product, first definitions of the shape are made during the conceptional design of the production system. We refer to the shape as workspace, the required floor space of machines or the active areas of handling appliances. The information is stored as written specifications, sketches or CAD data. Information regarding the shape of the production system is necessary for the concretisation within the development process especially for the place of work planning and the working appliance planning.

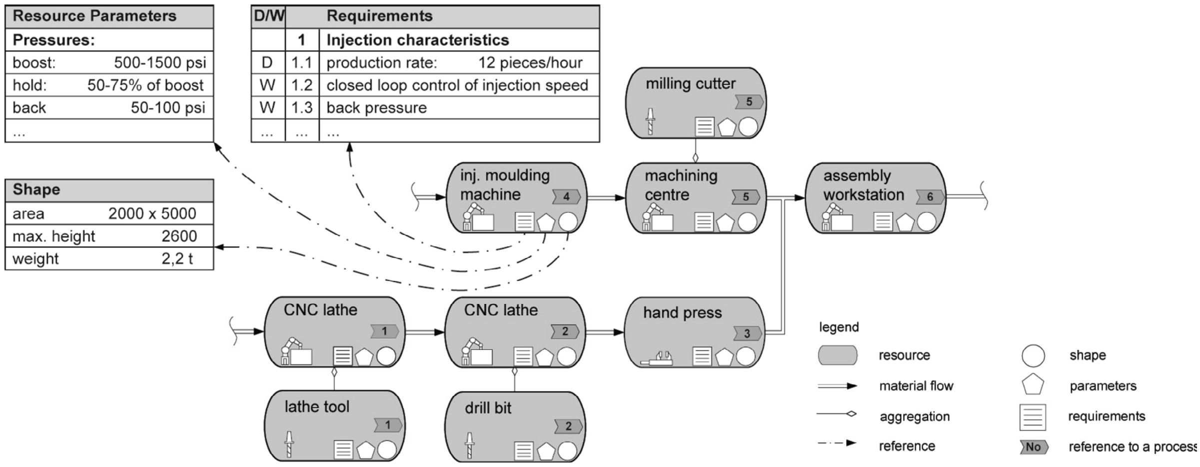

Figure 8. Depiction of the partial model resources of the miniature robot BeBot's production system (detail)

4.5 Interrelations between the partial models

The interrelations of the described partial models are shown in figure 9. We explain the interrelations using the example of the miniature robot´s drive wheel. As already mentioned, the conceptual design of the production system based on the three partial models of the product: requirements, active structure and shape. Within the active structure the drive wheel and its relation among other system elements are described. Requirements are made on the drive wheel that have to be fulfilled (1). The geometry and spatial relations of the drive wheel are specified within the partial model shape (2). Based on the active structure and the shape, the components to produce and their structural connections are derived. This information is depicted on the building structure (3). In this case, the building structure shows that the wheel and the bearing form the subassembly drive wheel. Therefore, manufacturing and assembly processes are required.

The process sequence is developed on the basis of the components, subassemblies and assemblies of the building structure (4). The hierarchical structure of the building structure is also reflected in the process sequence. In order to produce the wheel, suitable processes and their sequence are selected. In this case, a boring operation and a final machining are needed to produce the wheel. Finally, resources are allocated to the several processes (5). The linkage is represented as reference to the resource. Unique numbers are used to allocate processes and resources. In this case, the processes boring of the hub and final machining are allocated to two different CNC lathes.

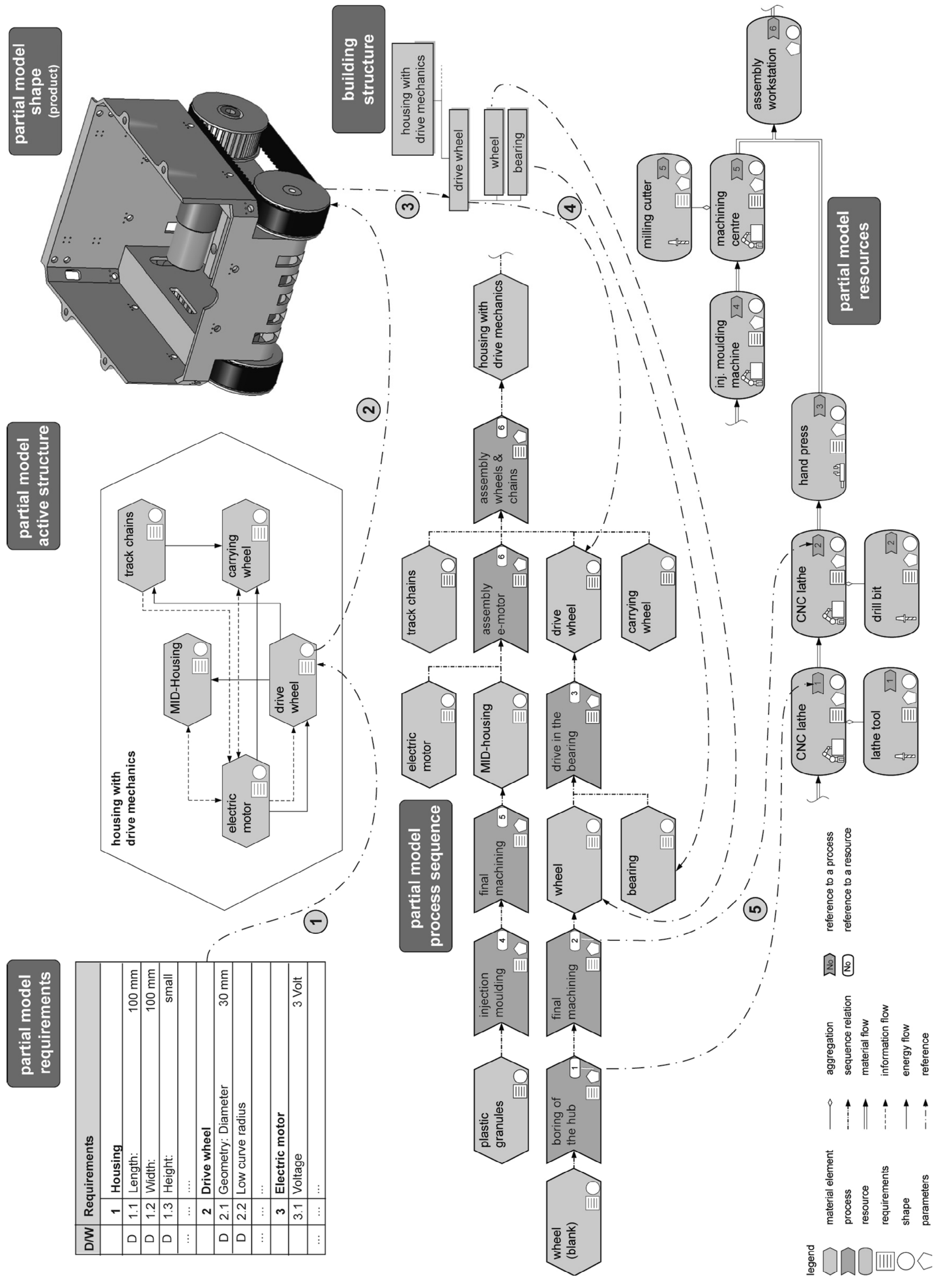

Figure 9. Depiction of the integrative conceptual design of the miniature robot BeBot's production system (detail)

5. Conclusion and future work

The example shows that already at an early stage of the development process the relationships between product and production system have to be taken into account. This is in particular necessary for mechatronic systems. A domain-spanning description of the principle solution of product and production system is needed. Therefore we propose a new specification technique to support the conceptual design of the production system based on the principle solution of the product. The principle solutions enable the consideration of relationships between the product concept and the manufacturing concept at an early stage of the product development process. The proposed approach maps these relationships and represents the necessary basis for the communication and cooperation of the participating specialists in the fields of product and production system development. Furthermore, the models allocate the information for an early validation of manufacturing costs, robustness and reliability. Overall, it is a very promising approach for a holistic system design.

The described approach constitutes the starting point of a production planning specification. Particularly in regard to production systems for mechatronic products, there is a considerable need for action. The application of the developed methodology requires a software tool, which supports the graphical and interactive description as well as the generation of computer internal models. These computer internal models are an essential prerequisite for the mentioned validation. Within the cooperative project VireS such a software tool is currently in development. In an initial step the partial models of the product´s principle solution are implemented. Afterwards the software tool is going to be extended by the aspects of the conceptual design of production systems.

Acknowledgement

This research and development project is funded by the German Federal Ministry of Education and Research (BMBF) within the Framework Concept "Research for Tomorrow's Production" and managed by the Project Management Agency Karlsruhe (PTKA). The author is responsible for the contents of this publication.

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