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SYSTEMATIC FOR FUNCTION-ORIENTED DEVELOPMENT OF SPATIAL CIRCUIT CARRIERS AND PROTOTYPES

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1. Introduction

Products of mechanical engineering and related industrial sectors, such as the automotive industry, are more and more based on the close interaction of mechanics, electronics, cybernetics and software engineering, which is commonly expressed by the term mechatronics. Modern automobiles, machine tools or airplanes are examples for these mechatronic systems or consist of such subsystems. By now, three categories of mechatronic systems are differenced, as shown in Figure 1.

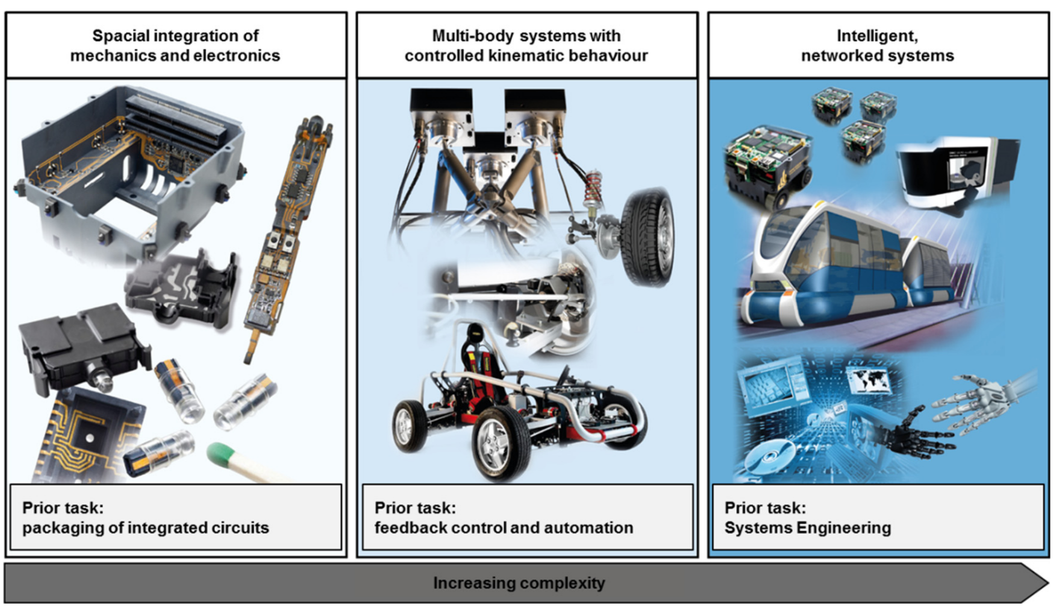


Figure 1. Three categories of mechatronic systems

The first category relies on the spatial integration of mechanics and electronics and is widely known as electronic packaging. The purpose is achieving a high density of mechanical and electronic functions within the available installation space. Such electromechanical parts, which are called integrated mechatronic systems, illustrate the basis for the second category of mechatronic systems (e.g. integrated sensors) [Feldmann 2009]. This second category deals with the controlled movement behaviour of multi-body systems. The focus lies on the controllers to improve the system behaviour by using sensors to collect information about the environment and the system itself. According to this, the improvement of the system behaviour represents the focus of cybernetics. Out of this information "optimized" reactions are generated and triggered by actuators. The third category of mechatronic systems is about intelligent, networked systems. Their aim is the consistent and omnipresent penetration of the physical every-day life by the virtual world. The term "Cyber-Physical Systems" stands for this kind of coordination, on which basis, especially in industrial applications; not only new intelligent products and production systems will be created, but also novel forms of intelligent services. The holistic integrated Systems Engineering during the development of these systems illustrates the main challenge [Broy 2010].

The electromechanical parts of the first category are very often the foundation for based thereon more complex systems of the following categories (e.g. integrated sensors). Within the development and production of such integrated mechatronic devices, requirements with regard to miniaturization, function integration, reliability and design are rising. Innovative technologies are necessary to meet these requirements. In this context the technology MID (Moulded Interconnect / Mechatronic Integrated Devices) is very promising. MID enables developers to design innovative components for mechatronic systems. By the integration of mechanical and electronic functions on one single interconnect device, packages with high functional density and considerable miniaturization can be realized. Applications from different industrial sectors like communication, automotive or medical industry illustrate the potentials and the high design flexibility in opposition to conventional technologies (e.g. flexible printed circuit boards) [Franke 2014].

A decisive factor for the implementation of existing ideas into successful MID projects is a precise knowledge and consistent use of the potential of integration by the MID technology is essential. However the knowledge and the possible potentials of the technology are often only a known to a few experts. These result on the one hand from strong dependencies between the design of the product and its production system; multifarious product requirements compete with restrictions of different manufacturing processes. On the other hand, a close interaction between electrical/electronic and mechanical design needs to take place. Both, mechanical and electronic designers have to deal with unfamiliar topics such as interconnect distances or mechanical stress. The MID-developer has to overcome these difficulties to generate an optimal product concept.

According to these challenges a consistent and systematic use of (virtual) models and prototypes within the product development is indispensable to ensure the reliability and functionality of the application and to support the collaborative work of the experts. Unfortunately today, virtual models are not a satisfactory substitute for physical prototypes, in terms of feasibility, interdependencies between mechanical and electronical Layout and process parameters. The various methods for producing physical prototypes have entirely different characteristics and can therefore only support partial aspects of the product in the development process. A systematic is needed that demonstrates the developer the ideal manufacturing process for each prototype, taking into account the specific requirements of the development phase.

Several design methodologies have been developed that should support developers with goal-oriented instructions for the design of MID-products. The disadvantage of these existing methodologies is the limited use of models during product development phase. Workarounds for the use of virtual models that are generated on different systems and then assembled manually and the unsystematic use of physical prototypes is state of the art. Since despite their possibilities modern construction tools do not focus on the integrative development of three-dimensional circuit carriers, a comprehensive the developer supporting systematic is essential, taking into account the early use of physical prototypes [Peitz 2008], [Kaiser 2009], [Goth et al. 2011], [Franke 2014].

This contribution is structured as follows: Section 2 will give a brief survey of the technology MID including a description of the main process technologies, prototyping alternatives and the state of the art of existing approaches for the development of MID-products. Our new systematic will be introduced and explained in section 3. Eventually, we will conclude our work and give a short outlook for future research.

2. Molded Interconnect Devices (MID)

The MID technology features advantages like 3D design freedom, high reliability and reduced manufacturing costs. Moulded Interconnect / Mechatronic Integrated Devices (MID) are three-dimensional circuit carriers with integrated mechanical and electronic functions. In addition optical, thermal and fluidic functions can be integrated. The circuit board is usually made of a three-dimensional injection-moulded part that can be designed (almost) freely. Mechanical features such as snap connections or vents can be integrated directly into the design. Typically a thermo-plastic material is used. For the production, a variety of different MID manufacturing technologies are available. Several different processes are combined in order to produce the base part, the circuit structure and the metallizing. Thus, interconnects and contacts are generated. This allows the direct application of electrical components, such as sensors. In addition, the metallization can be used for electrical functions such as shields, antenna structures or thermal bridges [Franke 2014].

2.1 Geometrical classification

The spatial freedom of scope enables an optimal adjustment of the electronic components according to the operational environment like optical sensors. The freedom of scope is limited though by the different production methods and process steps. These restrictions have to be taken into account during the development process. By a geometric classification a unified language is intended. It is based on the shape and arrangement of the structured and equipped surface. This concept can provide the necessary requirements for the manufacturing process. The classification is shown in Figure 2.

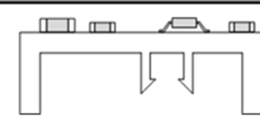
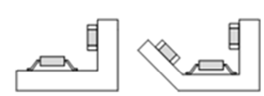
Dimension	Class	Characteristic	Sketch with assembly
2 ½ D	1A	planar process area 3D-Elements on the opposite side	
	1B	planar process area 3D-Elements on the same side	
	1C	multiple planar process areas	
n x 2D	2	multiple planar process areas with different angles	
3D	3A	ruled surfaces (e.g. cylindrical surfaces)	
	3B	free-forming surface	

Figure 2. Geometrical classification

Flat assemblies, like conventional printed circuit boards are classified as 2D and have a purely planar process area (Class 0, not in Figure 2). 2½D assemblies have a planar process area on a spatial structure (class 1A & 1B) or have various coplanar process surfaces (Class 1C). The nx2D-Dimension has several process surfaces that are arranged at an angle to each other (Class 2). Whereas assemblies in 3D allow the application of electrical structures on arbitrary ruled (Class 3A) or freeform surfaces (Class 3B) [Franke 2014].

2.2 MID manufacturing

A remarkable characteristic of the technology MID is the diversity of the different production processes (Figure 3). The first three process steps “Production of interconnect device”, “Structuring” and “Metallization” are necessary for the creation of the basic body part of a MID. The forthcoming "Connection process" is relevant for the integrated circuit packaging. The combination of suitable and reliable technologies is called MID process chain. Figure 3 shows the general MID process chain, called reference process for MID, and available technologies for manufacturing of MID-parts. Though, some technologies fulfil not only one process step [Franke 2014].

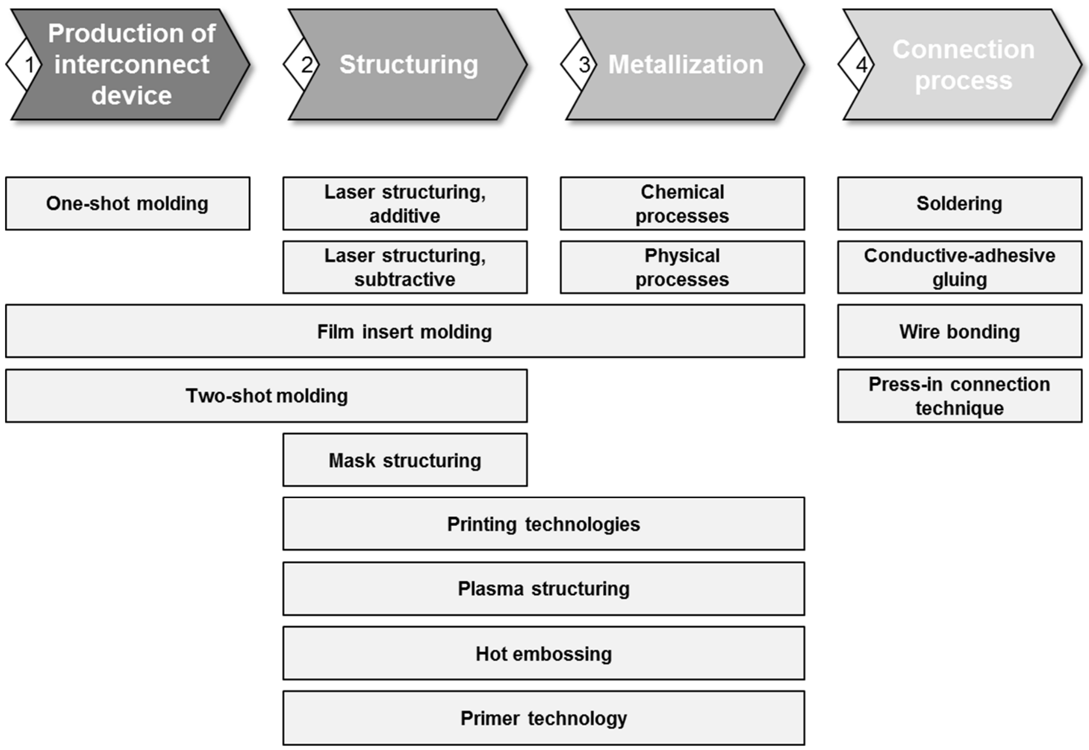


Figure 3. Reference process MID

The Production of the interconnect device is carried out at the beginning by means of the 1-Component or 2-Component injection moulding process or the film insert moulding. Within the 2C process, the circuit carrier is generated by two consecutive injection-moulded processes creating one component. In this case one component can be metallized so that the interconnect structures are already set by the injection moulding process. At the 1C injection moulding only the main body of the circuit carrier is injected. The generation of the interconnect layout is carried out in additional processes. The film insert moulding uses already structured and metalized foils. These are mechanically reinforced by an insert moulding with plastics.

The next process step is the structuring of the base body. Within the laser structuring a laser structures the circuit layout on the surface of the plastic. It can be distinguished between additive and subtractive laser structuring. At the additive method, the metallization is carried out after the structuring. The subtractive process requires a full surface metallization, which is structured afterwards. The hot embossing combines the two process steps of structuring and metallization. With the help of an embossing punch, which reflects the circuit layout, an already-coated metal foil is then impressed on the base body [Feldmann and Goth 2008].

The connection technology (assembly and packaging) consists of the coating / equipping and the adjoining connection to the structured and metallized circuit carrier. Various processes can be used again. The Step is used for the application of the electronic components on the base body. The stages are subdivided into the following:

- application of a bonding medium (solder or conductive adhesive)
- equipping with electronic components
- creating a connection between circuit boards and components

There are strong dependencies between the MID product and its manufacturing process. The restrictions of the MID manufacturing limit the solution space for the design, since they constitute restrictions on the product shape. Furthermore, strong restrictions arise from the various process steps, which are linked in a complex value chain and partly distributed over more than one company. The resulting interactions and dependencies significantly affect the quality of MID products. For example, surface quality of the plastic base body affects the adhesive properties of the metallization and, consequently, the reliable connection of the applied SMD components.

2.3 Field of action: Development of MID-parts

The Development of technical systems is generally assisted by several procedural systems with different focuses (VDI/VDE 2221, Pahl/Beitz, VDI 2422, and others). The specifics of the development of mechanical electrical/electronic modules are largely taken into account in VDI 2206 - Design Methodology for Mechatronic Systems. Within the development and production of integrated mechatronic devices, requirements with regard to miniaturization, function integration, reliability and design are rising. Innovative technologies like MID are necessary to meet these requirements. However, the potentials of the technology are accompanied by various challenges within the development. These are resulting on the one hand from strong dependencies between the design of the product and its production system as well as multifarious product requirements compete with restrictions of different manufacturing processes. On the other hand, a close interaction between electrical/electronic and mechanical design needs to take place. The developer has to overcome these difficulties to generate an optimal product concept [Franke 2014].

Methodological approaches help MID developers utilize the potential of the technology optimally. The focus is on the one hand on the guidelines that define limiting values and support a design suitable for production. On the other hand collections of proven solutions, for example in the form of design catalogues, are used. Preferences for production and feasible design opportunities cause a solution-oriented product design. Prototypes support these methodological approaches. [Jürgenhake et al. 2014]

The design guideline provided by the company LPKF for example provides reliable parameters and recommendations with respect to a production-oriented product design for the development of MIDs in laser direct structuring technology. These are based on the technical parameters of the systems involved in the process and on the experience of the company in terms of already implemented applications. The design guideline takes into account both the development of the product and the manufacturing equipment involved. The LDS-MID-developer receives a guideline that comprises the process steps of injection moulding, structuring, metallization and connection [LPKF Laser & Electronics AG 2010].

In construction catalogues established and proven solutions for specific constructive tasks are collected with the aim to support the developer in the design process. There are different catalogues, which differ in terms of their content, the form of representation and the degree of concretization [Pahl et al. 2007]. Regarding the development of spatially integrated circuit carrier a MID design catalogue has been developed [Peitz 2007]. The latest trend in the field of supporting methodology are so-called MID-features that provide specimen solutions for MID products developed on the basis of systematic product development approaches and analysis of existing applications. They assist developers in that they provide integrative descriptions of design possibilities and the applicable rules for manufacture. Comparing the features with product requirements is a way of deriving design concepts and possibilities for the implementation of individual product functions [Franke 2014].

The disadvantage of these existing methodologies is the limited use of models and prototypes during product development phase. As mentioned a complex problem exists in this context: The dependencies between the different process steps are often not directly visible. Especially restrictions from single processes exclude subsequent manufacturing steps. Generally, the developer is often faced with the decision to select the correct manufacturing process for the product and the corresponding prototype according to the requirements to be verified. A methodical procedure is necessary to assist within this selection in order to meet the outlined requirements.

3. Development of MIDs and MID-prototypes

To meet the outlined challenges for the development of MID-products we invented a systematic taking into account the use of early prototypes. Therefore we analysed possible manufacturing process steps and determined their general suitability for the MID and the MID-prototyping correspondingly. In the next step, we developed MID classes that reflect the different requirements on prototypes and models in the product development process and associated the manufacturing processes respectively.
Subsequently we observed the MID functions and their possible solution elements according the MID design catalogue and their potential time when they should be verified during product development. For Example requirements on the shape have to be covered at an early stage, unlike electronic functions. Finally we brought it all together and associated the MID-functions with the manufacturing processes and prototype classes.

3.1 Manufacturing MID prototypes

The conventional production of MID applications by an injection moulding process is time consuming and expensive. Therefore, the efforts of industry and research show the significance of MID prototyping. Prototypes allow a shortened development process during product development, to recognize errors early and to reduce follow-up costs at a later development step. The prototyping technologies offer different opportunities for the process steps within the reference process. In particular we identified a variety of options for the production of the interconnect, shown in Figure 4.

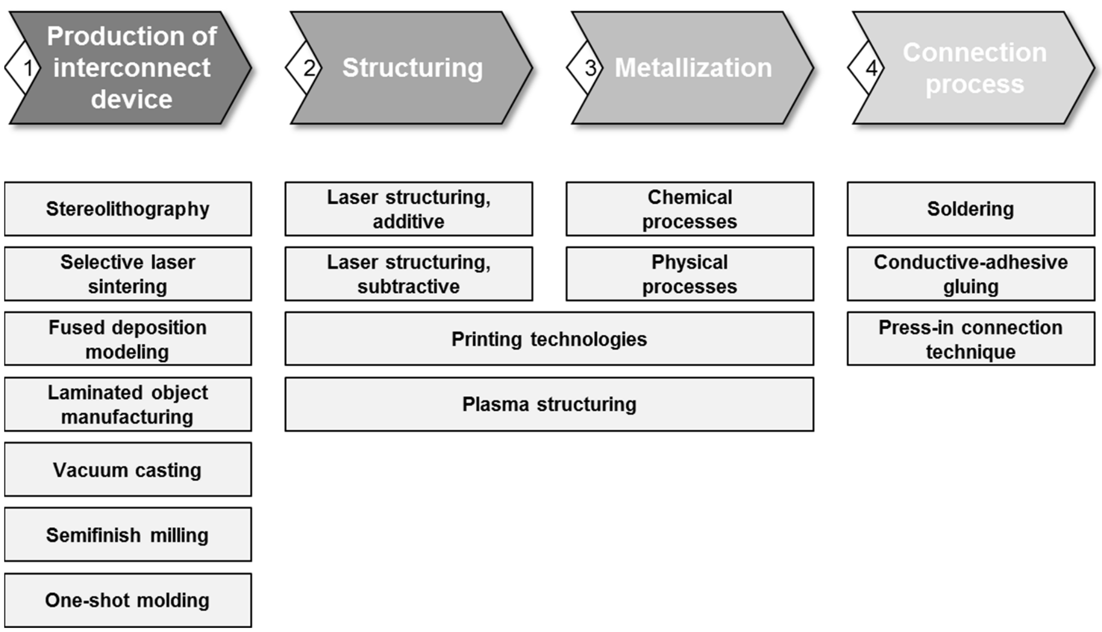


Figure 4. Reference process for MID-Prototyping

The generative manufacturing processes (stereolithography, selective laser sintering, fused deposition modelling and laminated object manufacturing) are all methods that produce the desired geometry by joining together several volume elements. These volume elements are preferably layers of equal thickness. The generative procedures can be divided into applications for the production of prototypes and models (rapid prototyping) and for the production of products (rapid manufacturing). For the production of tools or tool inserts (rapid tooling) these procedures are also used.

The generative procedures offer a variety of potentials, which are mainly attributable to toolless manufacturing. They offer an enhanced design freedom. Generative manufactured products must not take into account geometric and manufacturing limitations of today's serial methods such as injection moulding or milling. By the layer structure principle, almost any structure can be manufactured [Gebhardt 2013].
This advantage is often accompanied by significant drawbacks, such as the limited choice of materials, rough surfaces or reduced mechanical stability. For this reason, intermediate steps must be carried out, such as surface treatments or coatings, in order to perform the subsequent process steps after all. The existing manufacturing technologies and the purposefully combination of these process steps for MID prototypes cover different requirements. As a result and as no technology exists yet, which combines all benefits entirely; the choice of procedure requires awareness of all potential options.
The basis of an MID product is the three-dimensional circuit carrier. It meets the essential mechanical and electrical functions, such as the transmission of forces, packaging and contacting of electronic components or shielding from electromagnetic fields. Different functional elements are used to fulfil the different functions. With regard to the mechanical properties of the base body the demands on the material used are commonly investigated in the first place. For the MID technology it has to be taken into account that the body needs to combine the demonstrated needs of conventional printed circuit boards and moulded plastic carriers. The interactions that occur have to be considered and harmonized in terms of prototyping.

3.2 MID prototype-classes

A first aspect for the classification is the geometrical design of the basic body. With the increasing complexity of the spatial structure greater demands on the manufacturing process are provided. Especially in three-dimensional structures accessibility and achievable accuracy must be guaranteed in order to produce meaningful prototypes. With regard to the subsequent mounting of electronic components, the accessibility of the process surfaces and the possibility of exact positioning of the individual elements has to be granted. For this reason, high demands on the surface quality and dimensional accuracy of the process areas are set accordingly. With generative processes the process areas should be aligned horizontally to avoid the procedural typical step-effect. In addition, predetermined tolerances with regard to the process-specific wall thickness and layer thicknesses have to be observed and complied accordingly. Holes and curves should be placed if possible in building-direction and acute angles should be avoided. When designing the basic body thus the exact requirements for dimension, surface finish, dimensional accuracy and tolerances have to be defined, at least roughly. These limit the choice of the applicable procedures. In the verification of suitable material, it behaves similarly. If the MID product is exposed to high temperatures or an acidic environment, heat-resistant and chemical-resistant materials should be used accordingly. For the reliable fulfilment of the desired functions, the necessary mechanical and electrical conditions must be defined and proper methods selected. From the presented interdisciplinary conditions requirements have been revealed for all process steps, shown for example for the structuring process in Figure 5. They consist of the general requirements for the structuring. In this case two aspects are particularly relevant, the laser system and the circuit trace design, and the demands of the structuring on the base body production.
In the early stages of prototyping generative processes are used to obtain fast first results primarily. Throughout the product development a change is made to more accurate, production-based methods such as semi-finished milling or molding. Basically, the method used should build up consistently on each other to maintain the gained discoveries and design changes on the prototype and the product respectively. It is important when changing on injection moulding the altered flow and warpage behaviour of the material has to be taken in to account for example. The base body must be adapted to the new procedure accordingly. The focus is then on the higher demands on the achievable accuracy and dimensional accuracy of the technologies used.

MID-structuring		
Base body	**Laser system**	**Circuit trace design**
Incidence angle	Distances to circuit traces	Trace width
Accessibility	Distances to bevels	Ampacity
Fixation of the component	Distances to walls	Trace layout
Focus tracking at bevels	Distances to solder pads	
	Distances to functional surfaces	

Figure 5. Requirement criteria for the Process Step MID-structuring

A classification for MID-prototypes has to take the changing requirements throughout the product development phase into account. Different kinds of prototypes, from simple geometric models to final close to serial prototypes exist. The previous classifications by VDI 2221, VDI 3404 [Gebhardt 2013] and Eberhardt, Buckmüller and Kück [Franke 2014] do not consider the respective manufacturing processes and industry-specific requirements on the prototypes. Therefore we developed a classification for MID-prototypes taking into account these miscellaneous possible manufacturing procedures during the product development phases. Figure 6 gives an overview of our basic classification.

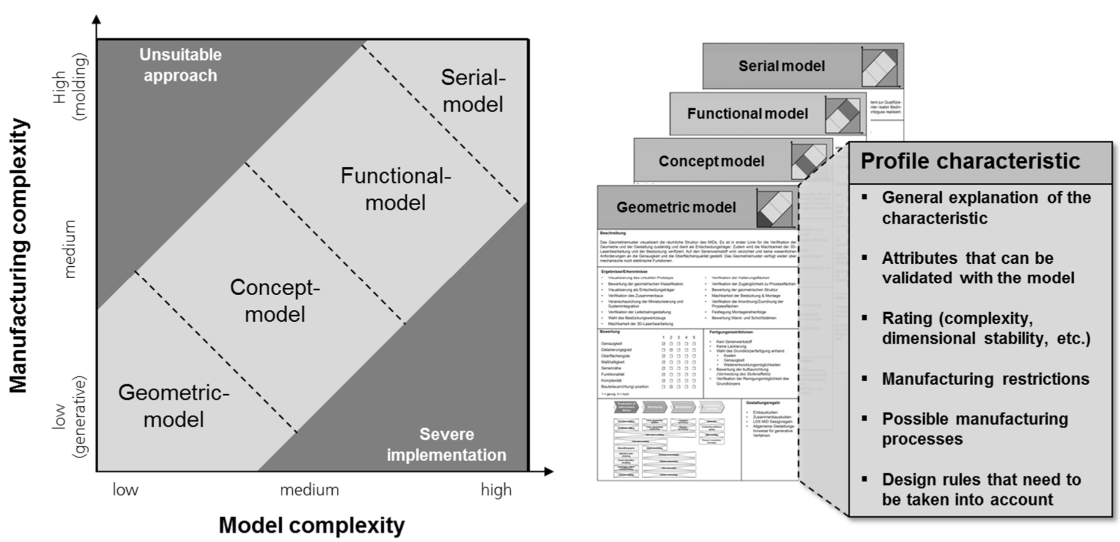


Figure 6. General MID prototype-classes

In a first step four general MID-prototype-classes have been derived:

- Geometric-model: The geometric-model is the simplest model and has no mechanical or electrical functions. It merely serves to evaluate and illustrate the geometric structure of MIDs. The dimensions of the outer shape and the orientation of the process areas can be verified by incorporation studies. Moreover, potentials of miniaturization and system integration are to be valued and to be used as decision-makers for the further development process.

- Concept-model: For the concept-model as opposed to the geometric-model, the use of serial material is imperative. Partial functions and important features that affect the material of the MID-module must be checked. The complete representation of the geometry is not necessary. Depending on the properties to be tested a partial representation of relevant process areas are sufficient.
- Functional-model: The functional-model illustrates the complete geometry and functionality of the serial product. It includes key findings of the geometric-model and the concept-model. The results to be obtained should have a high level of detail and a high significance for the final product. With the aid of the functional-model final reviews for structuring, metallization and packaging are performed.
- Serial-model: The serial-model corresponds to the final product and may differ in any significant feature. With the results of the serie-model, the new product is qualified and the pre-production approved.

Additive Prototyping is recommendable for quick and early assessments. Prototypes, which are close to serial production, need to be available as quickly and cost-efficiently as possible. The respective classes differ in their model- and manufacturing complexity.

Since many industries impose additional requirements on prototypes and model, we have also expanded the general prototype classes with industry-specific supplement characteristics. For this purpose the branches automotive, medical and IT and telecommunications were examined with regard to differing requirements on prototypes. The results were recovered in modular characteristics and can be complemented to the general MID Prototype classes as supplementary sheets.

In the automotive industry for example it can be revealed that both the concept-model and the functional-model have to be adapted for MID prototyping. The general geometrical-model and serial-model can be adopted without significant changes. For the concept-model the subsequent field of application of the final product must be analysed and the stresses and demands occur need to be derived. On this basis the required industry-specific testing procedures can be deduced. In addition, it must be specified whether the material must have high temperature properties. Depending on the application two different functional-add-on-models have been developed. The first variant describes the prototyping with high-temperature materials and the thereby to be considered activities on the manufacturing process. The second option involves the handling of the functional model without high temperature requirements. As an example Figure 7 shows the interaction of the general MID-classes and the supplement characteristics for automotive.

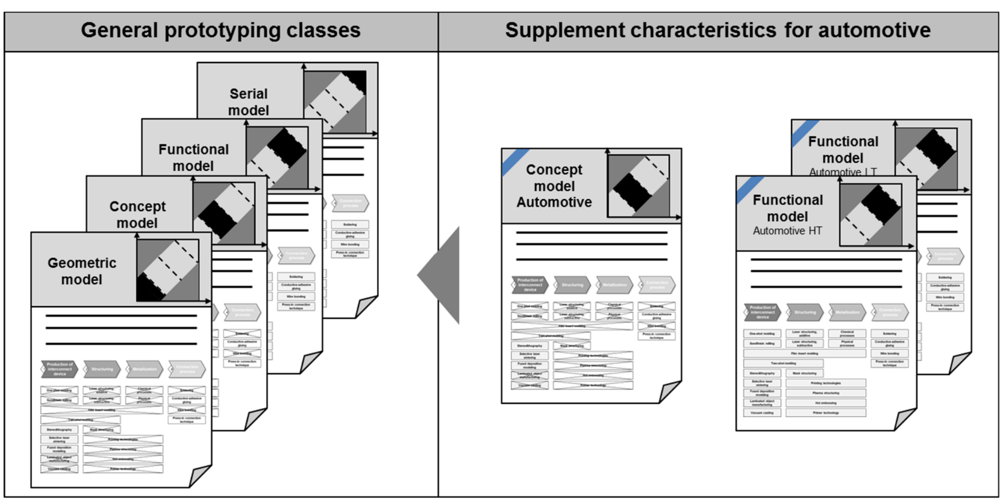


Figure 7. Interaction of general and supplement characteristics for automotive

The additional supplementary sheets gives the required information that is necessary to develop industry-specific prototypes. The sheets also provide information on standards, materials and manufacturing processes, and thus limit the options of the general categories partially.

3.3 Systematic

The presented systematic is based on a function-driven product development approach. In our case product-specific MID functions are identified, for example from construction catalogues, and then prioritized according to their urgency of hedging. We have extended an existing preliminary MID-construction catalogue from Peitz [2007]. The construction catalogue consists of two parts. The first part provides solutions for electrical MID-functions. The second part provides solutions for mechanical functions. The solution elements within the MID-design catalogue have been associated with favourable manufacturing processes. The developer selects and adapts the best matching solution elements for his task. Since some processes are unsuitable for the chosen solution elements, it limits the possible solution space for the MID-product and the corresponding prototype. The example of the clamp connection shows that selective laser sintering processes are unsuitable when the joint shall be used more frequently. After a single operation a smoothing of the material occurs. This results in a decreasing of the retaining force. By daisy chaining the product functions and the selected solution elements, we obtain a list of all possible manufacturing processes for the product and all prototypes where the chosen solution elements should be validated.
This function orientated preselection processes can then be combined with the corresponding prototype classes. Thus, at each stage of the product development process an ideal manufacturing process can be obtained. Figure 8 gives an overview of the interaction between construction catalogue and prototype classes

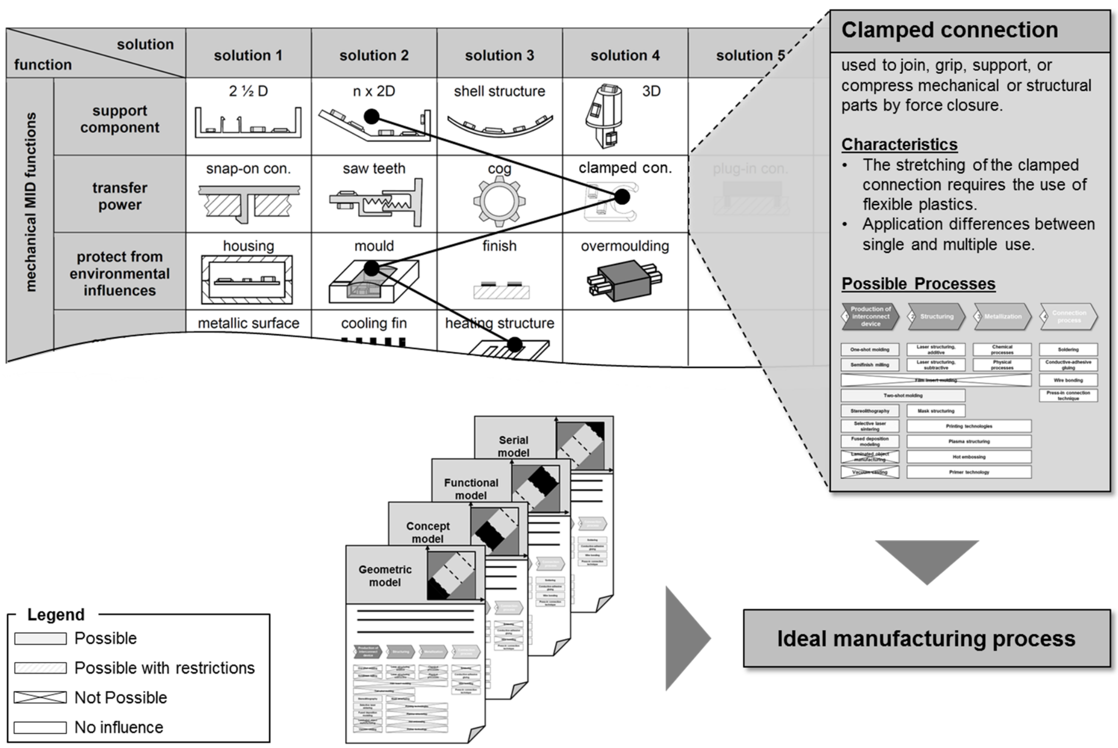


Figure 8. Interaction of construction catalogue and general prototype classes

This function-oriented approach supports the creative development process for the MID-product. At the same time the systematic provides a knowledge-based approach to MID-product development that can be used by inexperienced developers.

4. Conclusion and outlook

The MID technology offers great potential for innovative products. However, it lacks of a comprehensive market success. Several barriers obstruct this, in particular with regard to the development process: The complexity of MID-products due to their domain-spanning nature and occurring interactions between product and production system. At the same time various production processes with their respective restrictions carry out a complex development task. These interactions have to be considered during the design process. Since the design process of MID-product is the key aspect to successfully bring MID-ideas into market; the demand for early physical prototypes is obvious. They allow a shortening of the development process during product development due to detecting errors early and reducing follow-up costs. The aim of our approach was to develop a systematic that assists determining the ideal manufacturing process for a prototype at any stage of the product development process. Applicable MID-specific functions and solution elements have been analysed and the appropriate processes have been assigned. The developed prototype classes and the supplement branch-specific characteristics help to determine the correct procedure at each step of the product development process. The linking of solution elements of the MID design catalogue with concrete manufacturing processes allows a purposeful integrative development of product and production system. By combining these two approaches we have developed a systematic that helps inexperienced developers to create innovative MID products.

Future work will focus on the on the identification and specification of further functions and solution elements. This concerns in particular the aspects and characteristics of optical, thermal and magnetic functions with the corresponding manufacturing processes. Subsequently, costs have to be associated with each process. In addition, we are working on the implementation of the systematic within a software tool, to make it easily available for inexperienced developers. The tool will be validated shortly in a few MID companies. The focus is on a shortening of the development time, especially in business projects with inexperienced customers.

Acknowledgement

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