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Defining Requirements in Prototyping: The Holistic Prototype and Process Development

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Abstract

Designers and developers use prototypes in the product development process to gather information about the final product and its behavior as early as possible as well as to lower the risk of developing failing products. Literature describes prototyping as needed in general, but does not offer methodical approaches to the development of those prototypes themselves with the aim of gaining a maximum of knowledge. Prototyping is therefore primarily intuitive and iterative which often leads to an inefficient process. In most cases, no particular requirements to the prototype other than the requirements for the final product are specified. This paper therefore discusses the differences in requirements for different types of prototypes (e.g. functional, design and packaging) in different stages of the product and process development chain. The first part consists of the differentiation of types of prototypes, their relation to different stages of the product development process and accompanying requirements. Those types come in different forms and manifestations, for example virtual or real and focused or comprehensive. For each form and manifestation of the prototype, the developer has to specify different requirements. Those requirements depend mostly on the functions and phenomena the developer aims to investigate and the stage of the product development process. Nevertheless, the developer has to take into account that the manufacturing process of the prototype may differ from the process of the final product, which also leads to different requirements for the prototype. Another major difference between the final product and the prototype is the group of users or testers respectively. Depending on the group of testers, ranging from the developer himself over the management to the customer or even the end user, the developer has to anticipate the behavior of those testers and has to consider that behavior when specifying requirements. For example, a colleague, who also works on the product, may interact with the prototype in a different way than a randomized tester, who never saw the product before. Each prototype and subsequently each prototype testing phase then creates new information for the developer who is then able to transform the received information into new requirements for the next iteration of a prototype or the final product. Following these first results regarding requirements for prototypes, the paper discusses a holistic approach to the prototype and process development. The model is based on the holistic product and process development and visualizes the different influences and connections between the prototype development process and the prototype life cycle. The postulated model adapts the existing model and defines the prototype as a product itself, which then takes the place of the product in the product lifecycle chain. In addition, the prototype testing phase replaces the product use phase. This new model also includes the gained information from earlier versions of the prototype that the developer may respect in further iterations. The goal of this visualization is to provide an overview over the holistic prototyping process and the different requirements the developer has to take into account.

Keywords: requirements engineering, prototyping, mechatronic machine elements, design methodology

1 Introduction and motivation

Prototyping is an essential part of the product development process. It helps to increase the knowledge about the developed product and to ensure certain functions of the final product work and its properties are as intended. Therefore, literature and industry advise to use prototypes in the development process of new products. However, the term “prototype” is thereby used rather inflationary and rather unspecified regarding the type and extent of the prototype. In addition to that, the prototyping process itself is mostly driven by intuition and strongly depends on the knowledge of the developer. With intuition also comes a certain trial-and-error mentality leading to a rather inefficient and tinkering-based process so the outcome of the prototyping varies in success. To support this mentality but also to increase efficiency Boehmer et al. (2016) advise to provide special rooms (“Makerspace”) for intuitive and creative prototyping. This may lead to an increase in efficiency but the outcome of the prototyping process is still expected to vary depending on the intuition, knowledge and experience of the developer.

The usefulness of prototypes rises with the number of unknown factors and properties of the new product. Products that are based only on a small amount of or on no predecessor products are describable as more “radical” (Leifer 2006). The “radicalism” of innovations in general is a rather discussed topic with many authors stating that radical innovations do not exist and innovations are always based on predecessor products or reoccurring principles. For example, Altshuller (1998) describes the investigation of millions of patents and innovations for the TRIZ-Methodology with the conclusion that all these innovations are based on 40 innovative principles. Real “radicalism” is therefore highly discussable. Another example is the product generation development introduced by Albers et al. (2014) which is based on the conclusion that every new product has a comparable predecessor product. Each new product therefore inherits certain properties of its predecessor. However, Albers et al. (2017) analysed different generations of dual-mass-flywheels and come to the conclusion that the development risk rises if the overall working principle is changed severely. Another example of an innovation based on predecessor products is the development of a shifter unit for manual transmission shown in Figure 1. The shifter module was designed to analyse the effects of an adjustable hard stop that prevents the shift sleeve in a manual transmission from touching the shift fork and vice versa in engaged gear. The target of the prototype was to show that the mechanical vibration path from the synchronizer unit to the customer interface can be cut off to reduce the perceptible vibration level at the customer interface. Obviously, this design is not intended for mass production requiring the adaptation via prohibitively small adjustment screws. It is therefore a pure functional testing prototype. However, testing the prototype lead to the conclusion that decoupling the shift sleeve and the shift fork leads to a significant rise in user-comfort. For the final product, this function was realised via an additional passive vibration absorber consisting of a mass-spring-damper system at the top of the shifter module resulting in an innovative product.

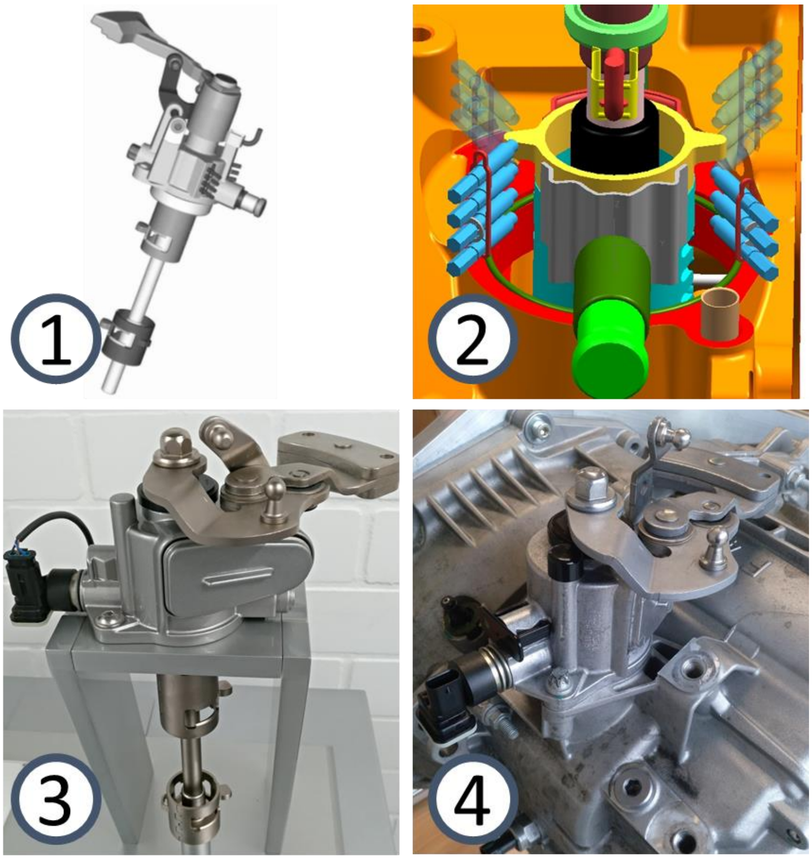


Figure 1: Overview over a generation based prototyping process leading to the final product. In this figure, one is the CAD-model of the shifter unit and two the detailed model. Three and four show the final product in a singled-out and in the final assembly position, respectively.

This paper focusses on the novel aspects of products that significantly differentiate them from their predecessor generations. All aspects subject to minor variations such as variation in shape or material are left undiscussed in here. The postulated methods in this paper are expected to be most effective and efficient when the knowledge gap of the developer about the product in development is rather high. This is the case, for example, if the new product is based on a low amount of predecessor products. An innovation in this context are mechatronic machine elements as introduced by Martin et al. (2018). Those elements integrate additional mechatronic functions, such as sensory functions, into machine elements to support a rather simple and extensive applicability of those functions in the overall system. The aims are to provide standardized solutions for the integration of sensors, actuators and communication devices in the overall product system and to gain information about the processes with a low amount of disturbance values. An example of a mechatronic machine elements is given by Schork et al. (2016) with the integration of a misalignment and torque measuring sensor in a helical beam coupling and an elastic claw coupling respectively.

Besides ensuring certain functions and properties of the final product work and are as intended, which falls in the category “learning”, prototypes also help with “communication” between the developer and the development team, with the management as well as with customers and users of the product. Furthermore, prototypes may constitute as “milestones” in the development process and the developer may use prototypes to analyse the effects of the “integration” of the final product in the overall system (Ulrich und Eppinger 1995). Prototypes for each of these categories may differ in their form and manifestation, leading to different requirements, which this paper discusses.

This paper focusses on physical prototypes instead of virtual prototypes because physical prototypes grand a higher usefulness regarding “complex phenomena”. Faithfull et al. (2001) conclude that these phenomena could be lost due to over-simplification. This is attributed to the circumstance that the outcome of testing a virtual prototype is only as good as the model taken as a basis for this prototype. The developer may disregard certain boundary conditions or simplify the virtual model too much, leading to deviant behaviour of the virtual model in comparison to the physical product. However, this also applies to physical prototypes, which present a model of the final product likewise and often deviate from the final product because of the added measurement tools. Matthiesen et al. (2016) therefore advise to use integrated sensors that do not alter the behaviour of the prototype in comparison to the final product.

An often referred to downside of physical prototyping is the time needed to manufacture the prototype. The risk is that the development process stands still while the developer is waiting on the outcome of the prototype testing phase and thus increasing the overall development time of the final product. In addition, producing prototypes relates to direct costs for material and manufacturing processes. However, in later stages the time invested in earlier phases and in testing with the prototype pays off, which is in conjunction with the aspects of frontloading. Furthermore, the standstill of the development process is avoidable by parallelizing the development of different parts of the final product.

Another downside of physical prototyping is the lack of resources in general. Besides the before mentioned resources time and money, also materials for the prototype and available manufacturing processes as well as the testing surroundings and equipment are limited which the developer has to take into account when developing a prototype. A possible way to reduce the consumption of resources is to reduce the extent of the prototype. Together with the unknown or partially known extent of the testing, the needed extent of the prototype is unknown, resulting in requirements for these prototypes being often unclear, unfinished or containing unnecessary entries.

Summarising this introduction it becomes clear that prototyping is an essential and broadly discussed part of the methodical development process. However, methodology for the development of the prototype itself and the related testing is no or a rather small part of the extensive discussion and literature. All of the above shows and elucidates the lack of methods and tools for the efficient development of prototypes. Regarding testing methodology, Boës et al. (2017) give an example of a taxonomy of testing activities that should help practitioners and educators to communicate with each other and point out that the discussion about a methodology for testing is highly relevant. Hannah et al. (2009) as well as Michaelraj (2012) also emphasize on the conclusion, that a taxonomy of prototyping activities helps in communication. Prototyping is an essential part of the testing process therefore a methodology for the efficient and effective development and use of prototypes is as essential as the methodology for testing.

To support the developer in developing physical prototypes, increasing efficiency and effectiveness as well as using of those prototypes, methods and tools are needed. This paper therefore discusses another take on the development of prototypes from a requirements based view, with the goal to define the needed requirements for a prototype that leads to a maximum knowledge gain quickly and thoroughly.

2 Different types and classes of prototypes and their relation to the product development process

Based on the Greek terms “protos” (*the first*) and “typos” *(kind of*), the term “prototype” stands for *the first of its kind*. In conjunction with the development of new products, developers, the management and customers use this term in a general and mostly unspecified way. However, this lack of specification, may lead to different objectives of stakeholders regarding the manifestation of the prototype as well as the outcome of the testing of the prototype. The manifestation of prototypes is expressible through its class and type. Ulrich und Eppinger (1995) postulate a classification of prototypes in a two-axis coordinate system with one axis being virtual – physical and the other axis being focused – comprehensive. Hoffmann (2013) also classifies prototypes in complete (comparable to comprehensive) and incomplete (comparable to focused) prototypes but switches the other axis to vertical (broad spectrum of functions but simplified) and horizontal (single but complex functions).

The type of the prototype often corresponds to the objective of the prototype, for example, functional, handling, geometry and processing prototypes. The types of prototypes therefore often imply the reason why the prototype is designed and are essential for a uniform understanding of the impeding task. In addition to that, the manifestation of the prototype hints at first requirements for the prototype and gives first connotations for the engineering of requirements.

Throughout generations of prototypes of the same product, the manifestation of these prototypes changes. To explain this further, an example of the development of a mechatronic elastic claw coupling is given. The idea behind this product is to measure torque that is transmitted via the coupling, for example, between a transmission and an electric motor. To achieve this, the conceptual design replaces one of the elastic elements of the coupling by an alternative elastic element, which consist of a bending plate and is equipped with a strain gauge. When torque is transmitted, the elastic element is deformed corresponding to the combined torsional spring rate of all the elastic elements. The overall deformation leads to a deformation of the bending plate. Measuring this deformation with the applied strain gauges and factoring in the torsional spring rate results in an information about the transmitted torque. The first prototype is a functional prototype classifiable as virtual and focused. Through the CAD and FEM model shown in Figure 2, information about the quantity and the characteristic two-dimensional distribution of strain was obtained.

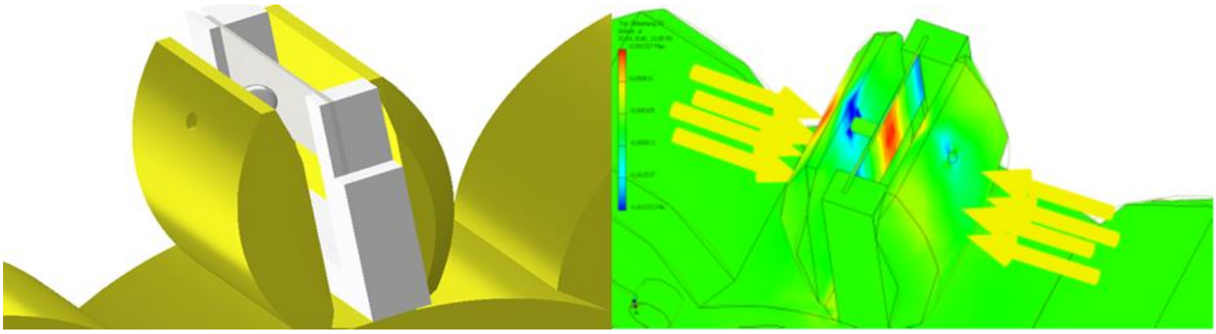


Figure 2. CAD model (left) and FEM model (right) of the measuring elastic element of the mechatronic elastic claw coupling. The FEM model shows the effects on the bending plate when torque is transmitted via the claw coupling

With this information, requirements for the next generation of the physical prototype as well as the final product were determined. The requirements focus on the transmission of force from the metal part of the coupling onto the elastic element. This transmission is required to be as direct as possible to eliminate unwanted effects of the elastomer and ideally in form of a single point of contact to eliminate effects caused by uneven force transmission. Figure 3 shows the first physical prototype of the mechatronic elastic claw coupling, which is able to proof the functionality of the torque measurement in a static system. Being developed for the use in a static testing field, the prototype is not required to rotate constantly resulting in cable-connected strain gauges being a viable option for the prototype. The length of the cable is only required to be long and flexible enough for the prototype to rotate 360° without interferences or disturbances of the cable. In the final product however, a solution must be developed to transmit the signal of the strain gauges even when rotating.

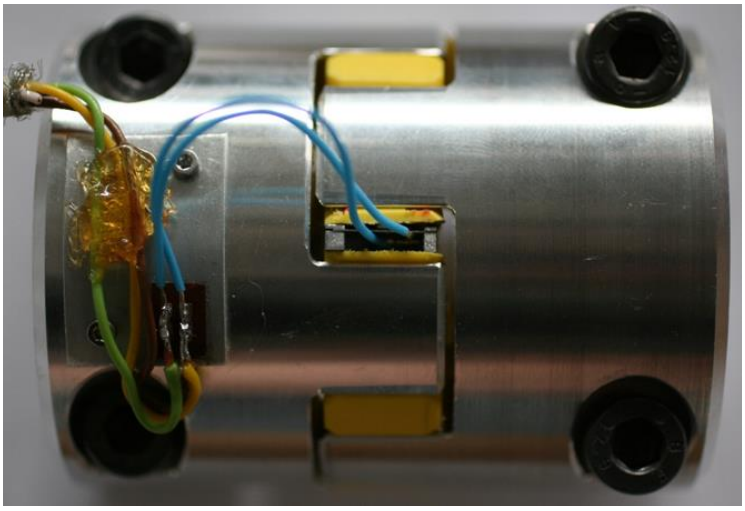


Figure 3. Physical prototype of the mechatronic elastic coupling to test the functionality of the replaced elastic element in a static test surrounding. The strain gauge is cable-connected allowing a single full rotation of 360° of the prototype

3 Introducing the holistic prototype and process development

The holistic product and process development model introduced by Birkhofer et al. (2007) describes the connections between the process chain of the product development and the process chain of the product life cycle, starting with the task of developing a product. The model on the one hand depicts that the product developer has to anticipate certain factors that result from the product life cycle, for example, the way the customer will use the product or how set materials influence the properties of the product. On the other hand, the model shows that the developer also influences the product life cycle, for example, the needed production processes to produce the product in development. In context with this model, developers may use prototypes to ensure their anticipation of certain processes, for example, with production prototypes to verify that the chosen production process is capable of producing the product with the anticipated quality. Another aspect of a production prototype is the question whether the production facility is capable of transporting the new product without collisions or not. To test this, a simple geometrical corpus with the anticipated shape or rather the maximal allowed dimensions is sufficient. In addition to that, developers are able to ensure the influence of their development, for example, using interface prototypes tested by the customers to analyse their interaction and the consequences of changing the interface. This leads to the conclusion, that prototypes are strongly related to the holistic product and process development model and that developers may use this model to identify the needed type of prototype to ensure their anticipation and influence on the product life cycle. In addition to that, the development of a prototype itself is describable as a product development of its own, resulting in minor adaptions to the model.

The holistic prototype and process development model shown in Figure 4 is based on the conclusion, that the development of a prototype is comparable to the development of a final product. First, in both situations a main "task" is given to the developer. In case of the product development on the one hand, this task is to develop a product that fulfils certain needs of the customer. In case of the prototype on the other hand, the task is to develop a prototype that in conjunction with the planned testing achieves the aimed for output. Both development processes rely on an ideally completed "clarification of the task". For prototypes, this clarification aims at finding the needed type and extent of the prototype, which both are connected directly to the list of requirements of the prototype. The determination of requirements for the prototype therefore is a major part of the clarification of the task. However, literature barely discusses or emphasises this determination.

The prototype life cycle in comparison to the product life cycle is subject to a few changes. First, the "prototype" replaces the "product" and instead of the "use phase", the prototype undergoes the "testing phase". This change elucidates, that requirements for the prototype differ from the requirements of the final product. "Material processing", "Production" and "Recycling and Disposal" of the prototype may also differ from the respective processes of the product, which the developer has to take into account. Especially with the possibility and rising prevalence of rapid prototyping technologies with various materials, the developer has to anticipate the different influences of the connected processes on the prototype and the conclusions of the prototype test phase. This applies to the determination of requirements for the prototype as well as to the preparation of the testing strategy. Regarding disposal on the one hand, the prototype presents less of a challenge than the final product because of its low quantity. Recycling on the other hand may be of interest when certain parts of the prototype, for example, standardised engines are due to re-use.

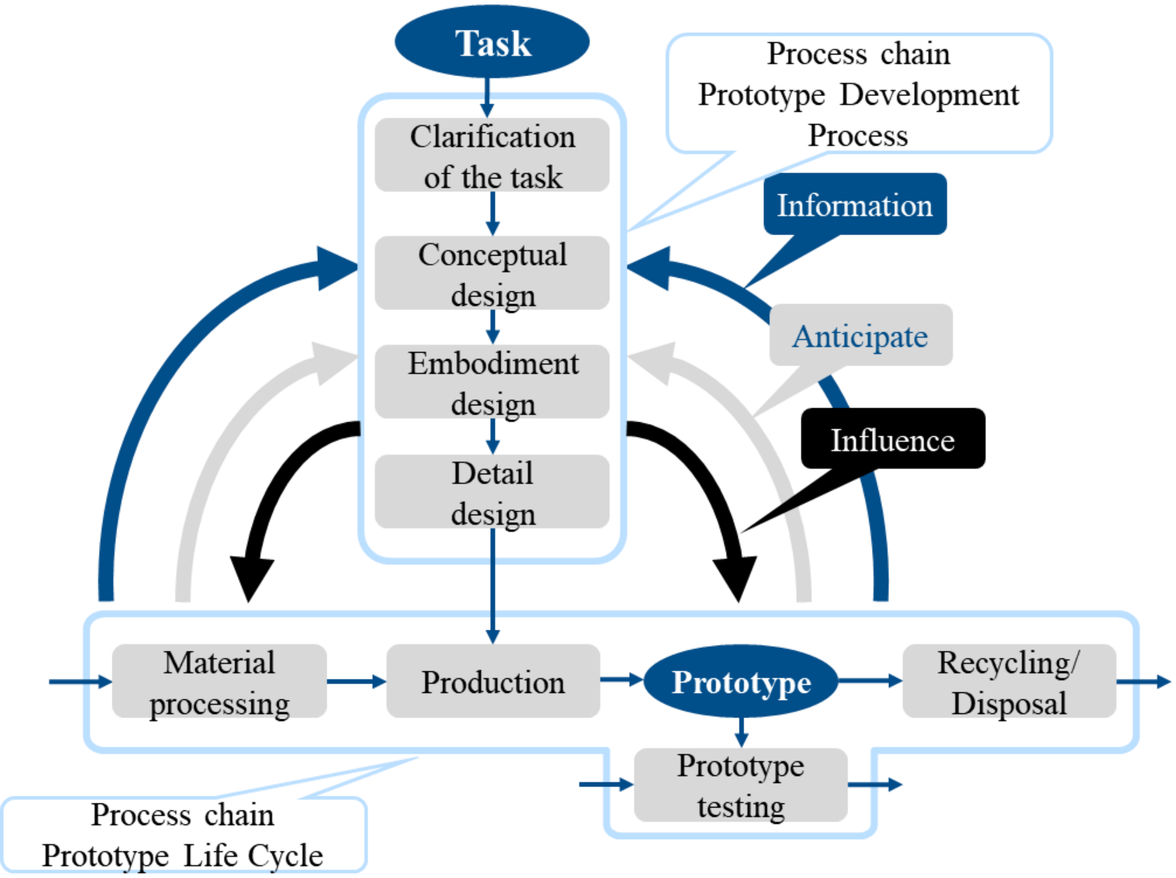


Figure 4. The holistic prototype and process development model (based on (Birkhofer et al. 2007))

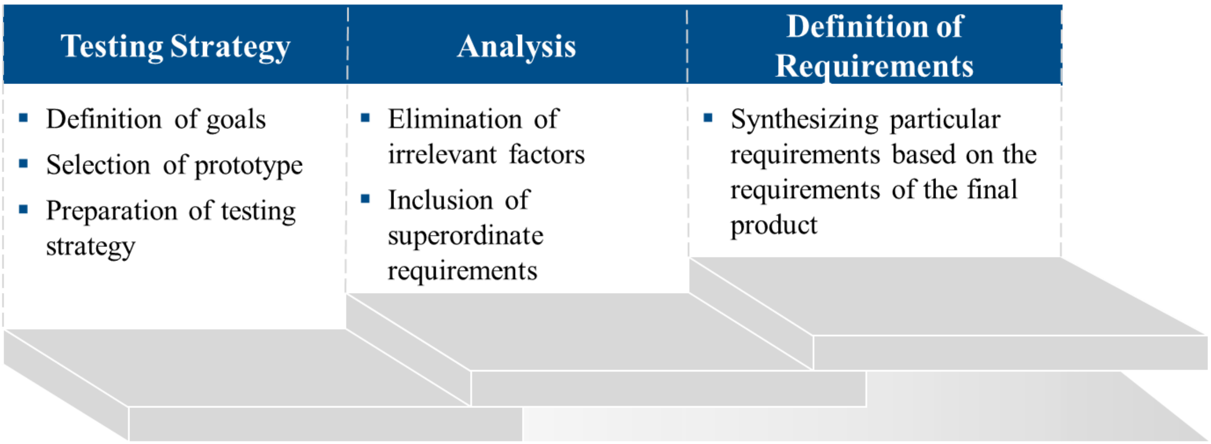
Prototyping is in general an iterative process. Each predecessor prototype provides new information about the prototype life cycle chain. Using this information, developers are able to identify new requirements for an upcoming prototype or the final product. The quality of the provided information strongly depends on the before developed prototype and the corresponding testing phase. By excluding certain environmental and boundary conditions, the information gained with the prototype is due to validation and verification. This also underlines the significance of a completed list of requirements for the prototype.

The example of the development of the mechatronic elastic claw coupling illustrates this model. For the two prototypical realizations, an individual prototype development process was completed. The results and conclusions of the first virtual prototype lead to information used in the development process of the second physical prototype in form of requirements. In the process, it must be observed that the information gained strongly depends on the prototype. In this example, there is no information gained about the material processing because the prototype does not focus on this subject.

4 Superordinate and particular requirements of prototypes

The holistic approach to the development of prototypes and connected processes shows the significance of the determination of requirements for the prototype that differ from the requirements of the final product. The requirements for the prototype originate from two main sources. The first source is the final product itself whereas the second source contains the testing strategy, the boundary conditions including resources and the group of testers. The separation of these sources is based on the assumption that the requirements resulting from the first source change with each iteration of the prototype depending, for example, on which aspects are planned to test. For this paper, requirements of this source are entitled “particular requirements”. In contrast to that, requirements of the second source are rather static and apply for each prototype, such as available resources, and are therefore entitled “superordinate requirements”.

Using superordinate and particular requirements helps to complete the list of requirements of the prototype. The determination of requirements is dividable in three phases. The first step revolves around the testing strategy. The developer defines the aspirated goal of the upcoming tests. This goal most likely implies a type of prototype, which the developer then selects. After that, the developer prepares a testing strategy for the prototype. The second and third phase, analysis and definition of requirements respectively, deal with the determination of superordinate and particular requirements for the prototype. Figure 5 shows the three phases in a descriptive way.



Testing Strategy
- Definition of goals
- Selection of prototype
- Preparation of testing strategy

Analysis
- Elimination of irrelevant factors
- Inclusion of superordinate requirements

Definition of Requirements
- Synthesizing particular requirements based on the requirements of the final product

Figure 5. Three phases of the determination of requirements for prototypes

4.1 Superordinate requirements depending on the surroundings, resources and group of testers

Superordinate requirements are independent of the prototype itself and apply to all prototypes of the final product. They result from the surroundings, for example, temperatures and free space on the test field, from the resources that are available, for example, funds, materials and time, as well as the group of testers, for example, members of the development team, the management or the user of the final product. Especially the group of testers should not be left out because each group may interact in a different way with the prototype leading to different feedback and different information (Matthiesen et al. 2009).

Superordinate requirements may also derive from set milestones a prototype has to fulfil. These milestones may differ between companies. Table 1 shows an exemplary excerpt of typical company set requirements for different stages of the development of automotive components with prototypes (Hohlfeld 2014). After reaching and passing D-Prototype status, the product reaches its final form and is ready for production and sale.

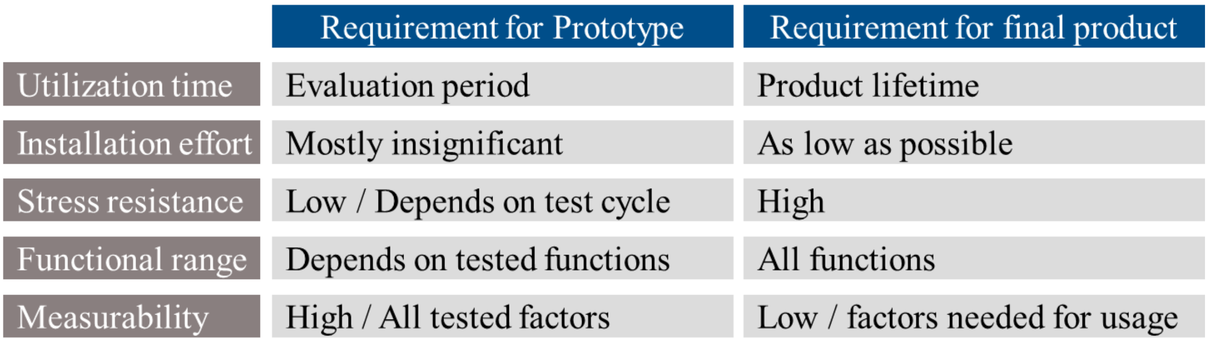
Table 1. Exemplary excerpt of typical company set requirements for different stages of the development of automotive components with prototypes (based on (Hohlfeld 2014))

	Usage	Quality	Production	Assembly
A-Prototype	Basic validation of the functionality of the concept	Low extent of functions Low durability	Manufacturing or changes to predecessor product Different materials	Hand assembly
B-Prototype	Validation of complete functional range	Geometry matches series First tests in vehicle possible	Production with prototypical tools Mostly final materials	Assembly with support processes
C-Prototype	Technical release	Same as B-Prototype	Production with series tools and close to series production processes Final materials	Assembly with series processes without automation of the assembly process chain
D-Prototype	Pre-series with validation of production reliability	Compliance to quality standards statistically proven	First samples produced with series tools and series production processes	Assembly with series processes and full automation of the process chain

4.2 Particular requirements synthesized from the requirements of the final product and the type of prototype

Particular requirements depend strongly on the requirements of the final product. Therefore, the developer has to determine those requirements for each new prototype or product completely new. However, the requirements for the prototype originate from the requirements of the final product wherefore the developer may synthesize the requirements for the prototype from the requirements of the final product. When doing so, the developer may not use all of the requirements of the final product for the prototype leading to an entire comprehensive prototype. On the contrary, the developer may keep the extent of the prototype relatively low, which also applies for the list of requirements. The main task for the developer therefore is to decide, which requirements of the final product are essential for the prototype or rather which properties of the final product need assurance. Gramlich et al. (2018) also emphasize on this approach stating that it is essential to consider and anticipate which material, process and product properties are essential for the success of the product in development and therefore require an in-depth analysis. To identify those “critical” properties, the developer may use methods, specifically designed for this task. Those methods factor in the uncertainty of different properties and the possibility to investigate their characteristics with virtual tools such as computer aided design and finite element method programs.

Figure 6 depicts examples of requirements of the final product that most certainly change their characteristics. In a large variety of prototypical testing, measurability of the product is required to be as high as needed to obtain information about the tested functions. In the final product however, the measured factors are reduced to those that are used for the functionality in general. Note that this list is neither encompassing nor do the entries apply to every prototype. It is obvious, that a prototype built to test montage processes requires the typically low required installation effort of the final product. For the mechatronic elastic claw coupling for example, the installation effort of the bending plate is rather high. Because of the prototypical nature, this is acceptable. Even though the installation effort is insignificant, useful information about a required installation process is gained through observing that the assembly of the coupling results in high forces on the elastic measuring element. For the final product, this influence must be reduced. Another synthesized requirement is the load capacity of the coupling. The final product has a load capacity of 90 Nm and the prototype only has a load capacity of 62 Nm. The functional range is also reduced based on the strategy to test the coupling stationary instead of rotating.



	Requirement for Prototype	Requirement for final product
Utilization time	Evaluation period	Product lifetime
Installation effort	Mostly insignificant	As low as possible
Stress resistance	Low / Depends on test cycle	High
Functional range	Depends on tested functions	All functions
Measurability	High / All tested factors	Low / factors needed for usage

Figure 6. General differences between the characteristics of requirements of the final product and the prototype (The differences are neither encompassing nor do they apply to every prototype).

5 Conclusion and further research

This paper emphasizes on the often-discussed topics of prototypes being essential for the product development process and the lacking in methodical approaches to develop the prototype itself. This paper therefore discusses the topic of requirements in the development process of a prototype and describes prototyping in a holistic model, including the final product as well as the occurring changes when developing a prototype of this product. To define requirements, the paper postulates a three-step approach consisting of the definition of the testing strategy, the analysis of the final product and its critical functions and the definition of requirements based on different sources. This aims at helping the developer to approach the development of the prototype more systematically and methodically, which is expected to be most successful with unexperienced developers as well as with the development of products that are new the developer, for example, when new fields of technology are involved. Furthermore, the paper emphasizes on the necessity and importance of an ideally completed list of requirements for the prototype to support developers to consider all aspects of the development of the prototype. The definition of requirements for prototypes may be time consuming therefore an abort criterion should be developed to keep the development time of the prototype low in order to keep the development time of the final product low. However, the development time of a single prototype may increase when refining the list of requirements. Nevertheless, this time is well spent regarding the goal to reduce the total number of prototypes needed to answer the proposed questions about the functionality of the final product. The next step is to validate and verify the discussed method in an industrial context.

The types of prototypes are not limited to the ones discussed in literature because for each goal a new prototype with a new prefix may be used. However, to support communication between the developers, customers and the management, specifying prototypes is useful. With this specification, companies are also able to define superordinate requirements the prototype has to fulfil that act as milestones. An example of these requirements and milestones is given with the explanation of A-, B-, C- and D-Prototypes.

Furthermore, this paper concludes that further methods are needed for the determination of requirements. Especially the identification of key or critical properties that should be ensured with the prototype and the identification of the therefore needed type and extent of the prototype is a key method in the efficient development of prototypes.

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