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Criticality-based planning of prototype sequences

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Abstract

The understanding of prototyping has changed in recent years to an approach that accompanies the product development process. This paper examines whether classic approaches from product development are also suitable for planning prototyping sequences. The stepwise process-oriented and the problem-oriented approach are discussed. A criticality assessment is proposed as a metric for the prioritization of the functional areas and a procedure is derived from this. The procedure is illustrated using an example. The result is discussed and future steps are suggested.

Keywords: prototype planing, prototyping strategy, criticality, design process, prototyping

1. Prototyping in product development

Product development is a multifaceted and iterative process that demands precision, innovation, and adaptability. One key element that plays a pivotal role in this intricate journey from concept to market is prototyping. Prototyping serves as a tangible manifestation of ideas, allowing designers, engineers, and stakeholders to evaluate, refine, and enhance a product before it reaches the final stages of production. The literature describes some approaches for planning individual prototypes at a single point in time or for structuring the prototyping activity. Ulrich and Eppinger (2012) describe a 4-step model here. Christie et al.,(2012) describe 9 factors and propose thirteen decision variables to consider when determining a prototyping strategy. These factors and questions focus on taking a design from concept to reality. They define the prototyping strategy as "*the set of decisions that determine what actions will be taken to develop the prototype(s)*" (Christie et al., 2012, p. 3).

(Camburn et al., 2015; Dunlap et al., 2014)propose a process for establishing prototyping strategies to help teams guide their prototyping efforts This approach was formalized and extended in 2017 (Camburn et al., 2017). They selected a set of five heuristics (or dependent prototyping strategy variables): 1. number of design concepts 2. number of iterations for each concept 3. scaling 4. isolation of subsystems or design of an integrated system 5. relaxation or rigid application of design requirements.

Another approach is the "prototyping for x framework" by Menold *et al.* (2017). It describes prototyping as an activity consisting of 3 phases: Frame, Build, and Test. This model was further developed by Hansen et al. (2020) into the "Prototyping Planner", in which they added an evaluation phase. This approach also structures the prototyping activities for individual prototypes.

These prototyping strategies relate to the use of prototypes within product development. However, they usually focus on narrow time windows in the early phase or on the construction of prototypes at a single point in time. Even though the understanding of prototyping has changed, prototyping is no longer defined as a single phase in a linear process. It is an iterative activity that encompasses the entire product development process (Menold *et al.*, 2017).

The latest efforts are to document prototyping strategies from industry (Hansen and Özkil, 2020). With the proto-mapping presented here, it is possible to document both prototype attributes and information at a system level, in particular the prototyping sequences. The sequence of prototypes refers to the chronological order of prototypes to be created, which can be linear, parallel or both. It becomes clear that the prototyping sequences in particular have an influence on the design result. Already Christie *et al.* (2012) stated that one of the decisions that is part of a prototyping strategy is whether to plan to develop a sequence of prototypes of a concept. No methods are described for the planning of these prototyping sequences at a system level.

If prototyping can be considered a continuous phase in the product development process, can established methods from product development also be helpful in planning prototyping activities in advance? The methodically stepwise process-oriented and the sub-problem-oriented approach should be considered (Bender and Gericke, 2020). The following question arises in detail:

- Which of the above approaches is suitable for planning prototyping sequences in product development at the system level?

In order to answer the research question, the first step is to analyze and discuss possible action sequences with regard to their suitability for planning prototypes. This is followed by an illustration of planning using the example of the development of a new machine element.

2. Sequences of action options

It is necessary to consider several functions and subfunctions when developing new products. The designer develops individual solutions to implement these functions. Therefore Fricke, (1993) generally describes two sequences of action: the systematic, stepwise, process-oriented, and the problem-oriented approach (Figure 1). In practice, mixed forms of these approaches often occur (also displayed in Pahl and Beitz (Bender and Gericke, 2020)).

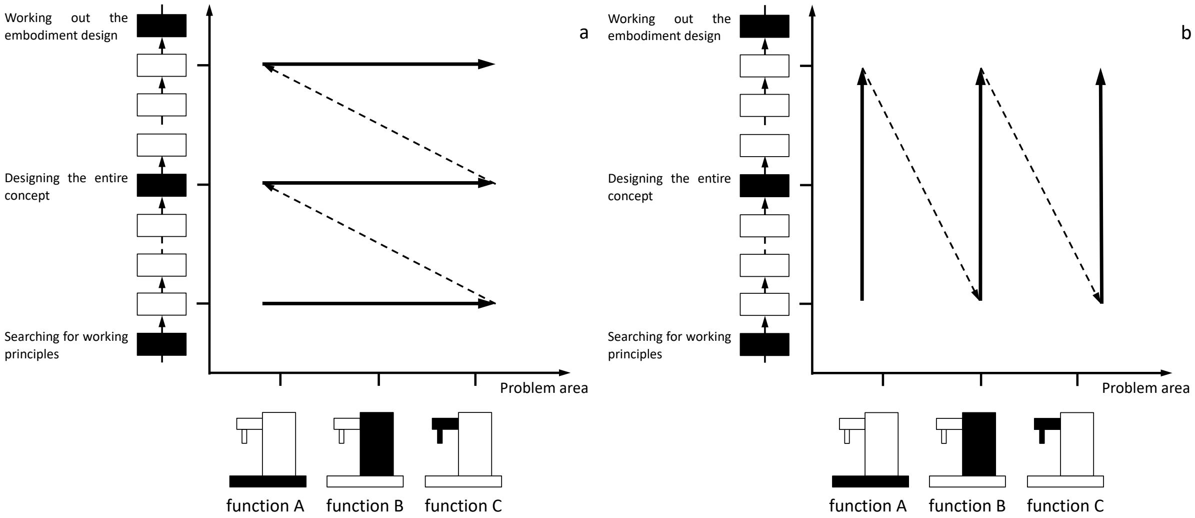

Figure 1. Different approaches to product development using the example of a tea-making machine: a) systematic, stepwise, process-oriented approach and b) problem-oriented approach

2.1.1. The problem-oriented approach

The problem-oriented approach (see Figure 1b) contrary focuses on one aspect or function of a product after another. So that the designer develops the different functional areas in sequences. For this approach, a wealth of experience is needed to arrive relatively quickly at a concrete solution. However, there is a certain risk of relatively late recognition of possible lack of compatibility between functional areas. Therefore, the problem-oriented approach is particularly suitable for products that have sub-functions that have little influence on each other.

2.1.2. The systematic, stepwise and process-oriented approach

The systematic, stepwise, process-oriented approach (see Figure 1a) examines and processes all functional areas in parallel from idea generation to final embodiment to find a solution. As the stepwise process-oriented approach considers the product as a whole at each stage, the disadvantages of the problem-based approach can be avoided if sub-functions influence each other. However, this approach is more time-consuming, as a broader systematic view is taken. The solution field must be narrowed down in good time as soon as a sufficient number of possible solutions are available.

2.1.3. Discussion

Based on the approaches described, there are two possible sequences for planning the increments. As explained in the previous section, the process-oriented approach takes a holistic view of all functional areas. This results in several difficulties. The increased time required to find a solution has already been mentioned (section 2.1.2). For the creation of the prototype, however, it also means that exactly one overall solution is created that already considers all functions and issues. With this approach, there are uncertainties in the prediction of interactions between the functional areas. Interactions must be considered in advance. The unknown interactions (unknowns) can be particularly problematic here.

If problems arise, a new holistic prototype must be created each time. A holistic iteration is also necessary if only one functional area is to change. This is reflected in increased time expenditure and rising costs.

Following the problem-oriented approach, we can advance the maturity level of each functional area individually. This means that we require less material and time for implementation and therefore lower costs. However, the interactions are even more difficult to plan as sub-functions may have already been brought to a high level of maturity and are then incompatible.

This approach also raises the question of which sub-function should be considered first. The functions must therefore be prioritized for this approach.

In principle, it makes sense to look first at the functions that contribute to a high degree to the functionality of the overall system. These already define certain properties for the system, which in turn can result in interactions. Furthermore, functions that have many interactions with other functional areas should also be considered. As these are not necessarily fully known and result in different risks, the prioritization should also take into account the level of knowledge of the function or the novelty curve. A multidimensional decision matrix is therefore required for prioritizing the functional areas to be considered.

3. Prioritising action options

When planning the prototyping activities, it became apparent that some kind of prioritization of the sub-functions was necessary to quickly increase the level of maturity and minimize prototyping activities.

Since the critical sub-functions in particular should be verified early in product development to minimize development risks (Albers et al., 2014), a criticality assessment was therefore carried out.

According to Schork et al., 2020 (based on Albers et al., 2014), the criticality of sub-functions can be measured using three parameters: **Novelty**, **technical difficulty** and **importance in the product** (see Figure 2). These parameters are weighted from one to three, with one being low and three being high. Low criticality of a sub-function (green) means that a maximum of two of the individual ratings are of medium importance. If one individual evaluation is of high importance, the function has medium criticality (yellow) and as soon as there are two high individual ratings, the function has high criticality (red).

"Novelty" assesses how much knowledge is available about a function. A low rating (1) means that experience has been gained or knowledge can be transferred from a similar use case. A high rating (3), on the other hand, means that there is no knowledge about the function and the mutual effects on other functions are unknown.

The "technical difficulty" assesses how much effort is expected to be required to map a function in a product. A high rating (3) means that it has far-reaching effects on the product. A low rating (1) is awarded if the function can be easily mapped and the interactions are evident.

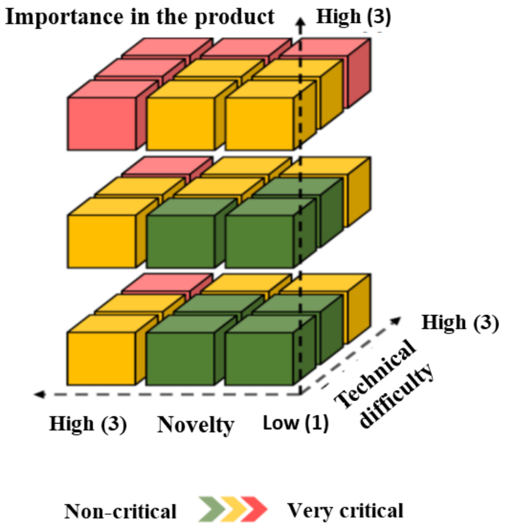

Figure 2. Criticality matrix and resulting criticality ratings

The "significance in the product" refers to the effects of partial or non-fulfilment of the function. If a sub-function is rated low (1), the impact is low. Strong impacts are to be expected with a high rating (3).

4. Analysing the system

In this paper, the sequence is now illustrated using the example of a new development of a machine element. The potential of additive manufacturing is to be exploited for a toothed belt wheel. The operating principle of a hydraulic clamping bushing (HSB) is to be integrated as a force-fit shaft-hub connection. Among other things, this would enable very fast assembly and disassembly.

4.1. Operating principle of the hydraulic clamping machine element

Hydraulic clamping bushes (HSB) belong to the class of frictional shaft-hub connections. Figure 3 illustrates the function of such an HSB using the example of an ETP Express bushing made of metal. The bushing is double-walled. The theoretical zero gap contains a very small amount of oil as a pressure medium. Tightening the screw in the flange increases the pressure inside the bushing. The lateral surfaces deform elastically, resulting in surface pressure that braces the adjacent shaft and the machine element. This operating principle enables very fast assembly and disassembly, as well as very precise axial positioning.

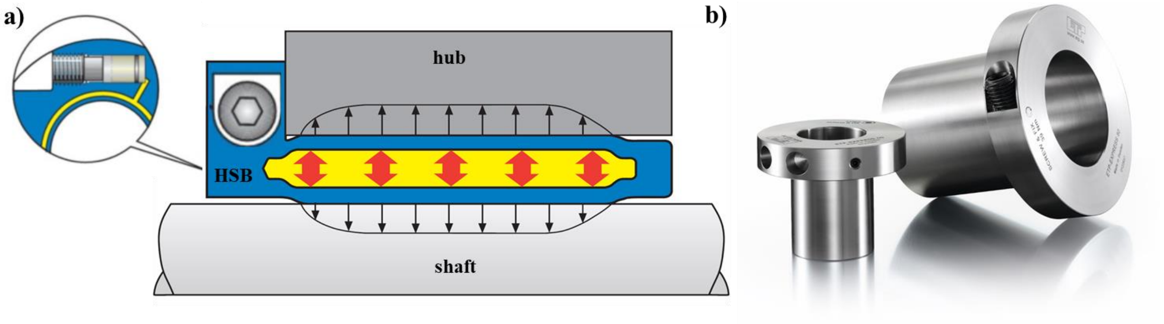

Figure 3. Hydraulic clamping bush a) operating principle b) ETP metal Express bushing

The idea for the new development was to utilize the potential of additive manufacturing and integrate the operating principle of a hydraulic clamping bushing (HSB) directly into a machine element. In a previous project, the functionality of an additively manufactured HSB (Figure B) was demonstrated and tested. A toothed belt wheel was selected as an example of the machine elements for further investigation.

4.2. Function structure

The first step was to analyze the functions and sub-functions to be implemented. These are summarized in the following function structure. The main function of the system is to transmit torque from the hub to the shaft or vice versa. For the following consideration, we will limit ourselves to the transmission from the hub to the shaft utilizing a toothed belt. The torque is thus applied via the pair of active surfaces of the toothed belt and toothed belt wheel (hub). On the other side, the torque is transmitted through the wall of the hub to the shaft.

For the torque to be transmitted, the clearance between the shaft and hub required for assembly must be bridged. This is achieved by applying hydraulic pressure to the cavity of the belt pulley. The pressure applied creates a force-fit connection by deforming the side surface. The play between the shaft and hub is eliminated and the resulting surface pressure enables torque transmission. The use case of hydraulic tensioning is illustrated in the following functional structure. It is assumed that the clamping element is already on the shaft and the toothed belt is fitted.

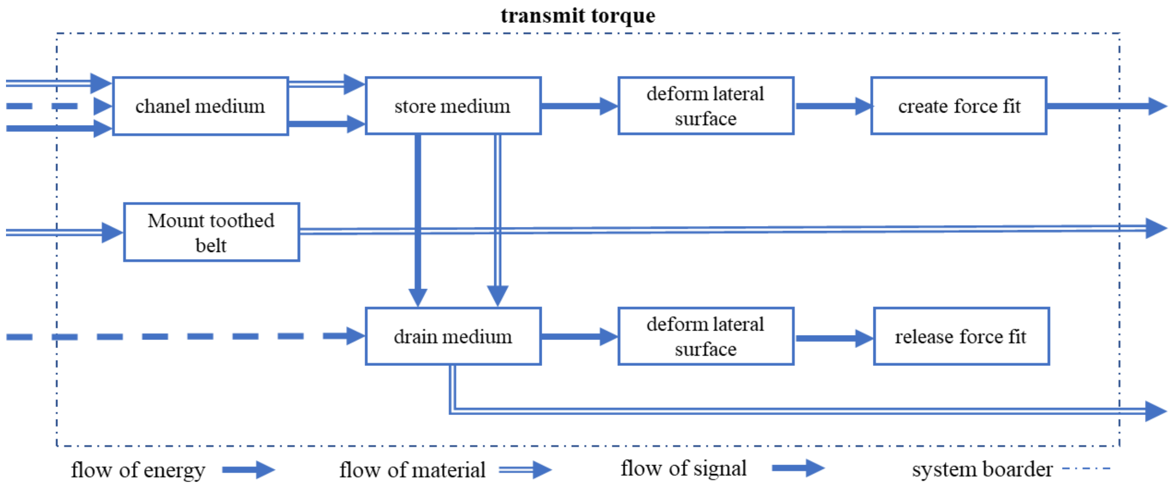

Figure 4. Function structure of the hydraulically clamping toothed belt

These include channelling a medium and storing a medium reliably (tightness). "Store Medium" also means that there must be a volume in which the medium is located. The applied pressure "deforms the lateral surface". This is intended to close the gaps between the shaft and the hub. This creates a force fit that should be reversible. To make this possible, it must be necessary to be able to drain the applied medium and thus the pressure. When the pressure is released, the lateral surface returns to its original position and the force fit is loosened. The entire system is intended to transmit torque via a toothed belt, which is why the belt must be accommodated.

4.3. Criticality rating

"channel medium" forms the interface through which a medium can be introduced. This is a valve. Valves are reliable and well-researched components. Due to the variations in valves, this sub-function is not considered critical. "Store medium" is classified as very critical; it is heavily dependent on the AM method and the manufacturing process. Failure of this sub-function leads to non-fulfilment of the overall function. Necessary changes can affect the entire geometry of the component. The lateral surfaces must deform sufficiently so that the surface pressure is high enough and the torque can be transmitted. The adjusting screws for the deformation of the lateral surface are the wall thickness and the structure of the wall, the operating pressure, and the rigidity of the material. "Drain medium" is considered unproblematic, as this can be achieved by unscrewing the valve. This should also loosen the connection. The timing belt has a complex geometry which, with the manufacturing tolerances, must correspond to the actual product of the timing belt pulley. This is why "mount toothed belt" is critical. The individual ratings are summarized once again in the following Table 1.

Table 1. Criticality rating

	function	Rating (novelty, technical difficulty, importance)	Criticality level
1.	Chanel Medium	1,1,2	low criticality
2.	Store Medium	2,3,3	high criticality
3.	Deform lateral surface	1,1,3	medium criticality
4.	Create force fit	1,2,3	medium criticality
5.	Drain medium	1,1,2	low criticality
6.	Release force fit	1,1,1	low criticality
7.	Mount toothed belt	1,1,3	medium criticality

4.4. Findings from the analysis of the system

The criticality rating showed that the sub-function "store medium" is essential and will most likely cause the greatest challenges. Without this function, the machine element is unable to fulfil its task. Various questions arise from the requirements and the functional structure. In some cases, the answers to these questions can be found through research. The questions that cannot be answered in this way provide the prototypes. The structure can be derived from these.

1. Which materials are suitable?
2. How can tightness be guaranteed for the selected AM process?
   a. Which parameters must be taken into account during design and additive manufacture?
   b. Which medium is suitable?
   c. Which valve is suitable?
   d. Is reworking necessary and what does it look like?
3. What is the exact geometry of the toothed belt pulley?
4. Which geometry is favourable for production and the function of the product?
5. What torque can be transmitted?
6. Illustration of the procedure using an example.

5. The planning sequence for the increments to be implemented is now set up for the example described

5.1.1. Problem-oriented approach with prioritisation

The starting point is the specified functions (see 4.2) and their criticality ratings (see 4.3). If a prototype is provided for the verification of each functional area a linear sequence results, as shown in the following figure (Figure 4). Iterations for individual functional areas are possible, e.g. prototype P0.1 to P0.n. Once a satisfactory level of maturity has been reached, the next functional area is accessed.

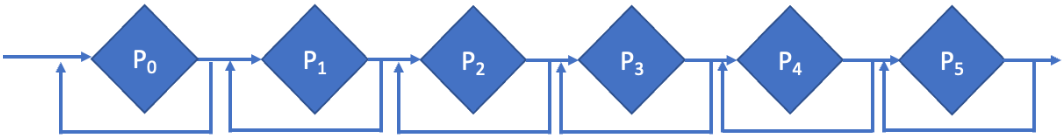

Figure 5. Prototyping cascade with a problem-oriented approach

The highest criticality is assigned to the functional area "store medium" (2) and this is therefore the first to be considered. At the next level with medium criticality, there are again three functional areas. These could be worked through one after the other. The individual ratings can be used to form a ranking.

The novelty is rated the same for "deform lateral surface" (3), create force fit (4) and "mount toothed belt" (7) and technical difficulty is only rated higher for "create force fit" (4).

As already explained when looking at the state of the art, combined approaches are used in reality. Due to the low scores for interactions, it would be examined whether prototypes could be combined. For further planning, a combined approach of a basic problem-oriented procedure with a section-by-section process-oriented approach was chosen. This is presented in detail in the following section.

5.1.2. Combined approach

In the combined approach, the critical functions are also processed first. This ensures that changes in the product can be implemented early on or that findings are integrated early on. Subsequently, less critical functional areas can be merged into prototype types so that further functions can be mapped at the same time with little additional effort. The information gain can thus be accelerated.
This approach resulted in the following sequence (Figure 6).

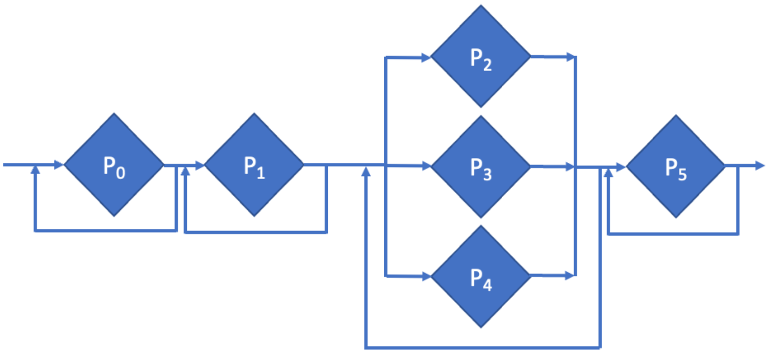

Figure 6. Combined approach of principle problem-oriented approach with sectional process-oriented approach

As already considered, the highest criticality is assigned to the functional area "store medium" (2) and this should therefore be considered first. To validate this function, it is necessary to test the components for pressure tightness for the selected AM process. A test geometry must be designed and modelled in an initial virtual prototype P0. The maximum test pressure is also determined. The second increment is the prototype P1. The test geometry is physically implemented and the influence of the process parameters is examined. An overview of the information on the prototypes is shown in Table 2.

Table 2. Overview of the prototypes

Prototype	P0	P1	P2	P3	P4	P5
function	2	2	7	3,4	1,5,6	1,2,3,4,5,6,7
type	virtual	physical	virtual	virtual	virtual	physical
aspects	CAD modelling	defining the test volume	modelling the gearing	modelling HSB	simulation of force application	additive manufacturing
	Simulation internal pressure	Investigation of AM manufacturing parameters	Adjustment of the geometry	Simulation of elastic deformation and max pressure	Modeling of combined clamping and machine element	Mounting the valve and pressure gauge
Outcome	Determination of maximum operating pressure	Determination of AM-process parameters for pressure-tight results	Defined surface for toothed belts	Proven functionality of the clamping element	Strength verification and completion of the CAD model	Holistic prototype for testing

This is followed by the combined approach in which functional areas with a lower criticality are merged. For example, the interface to the timing belt is analyzed and modelled in parallel in P2. This information is used to create a CAD model in P3. This is then used to simulate the function of the tensioning element in the combined hub (P3), taking functional areas 3 and 4 into account. Furthermore, the now holistic model is examined concerning force application and transmission (P4). Functional areas 1, 5 and 6 are considered simultaneously, allowing interactions to be mapped.

The knowledge gained is incorporated into prototype P5. Here, a holistic model is physically implemented, which takes all functional areas into account in parallel. This prototype was then used for validation on the test rig about the transmitted torque.

5.2. Representation of increments

The prototypes of the planned sequence range between the virtual and physical dimensions as well as between focused and comprehensive dimensions. The sequence with their embodiments is visualized in Figure 6.

Planning starts in the virtual world with the focused prototype P0. A pressure vessel is modelled and simulated here. The aim is to determine the safety value when different test pressures are used. It should be noted that, depending on the quality of the layer bond, only around 60% of the material's insertion limit is reached between two adjacent layers (Butzke, 2019).

The tightness and thus the pressure application is process-dependent and must be verified experimentally. Therefore, the change to the physical takes place for prototype P1, which is also still focused on one aspect. Samples are printed at different flow rates and the leakage rates of the samples are then examined. It is noticeable that the dimensional accuracy of the components and the surface quality decrease as the flow rate increases. At a later stage, this will require reworking of the surface. An additional burst test for the layered composite shows that reduced material parameters of around 25% can be expected for further simulations. In prototype P2, the tooth geometry is compared with that of the belt manufacturer and modelled in preparation. This is again done in a virtual dimension.

The knowledge gained is incorporated into the next prototype P3. Although this is still in the virtual world, it is already further along the " comprehensive" axis, as several partial aspects are taken into account. The clamping machine element is simulated with an operating pressure of 12 bar. Furthermore, the wall thickness of the inner side is varied, which forms the force fit during operation through elastic deformation.

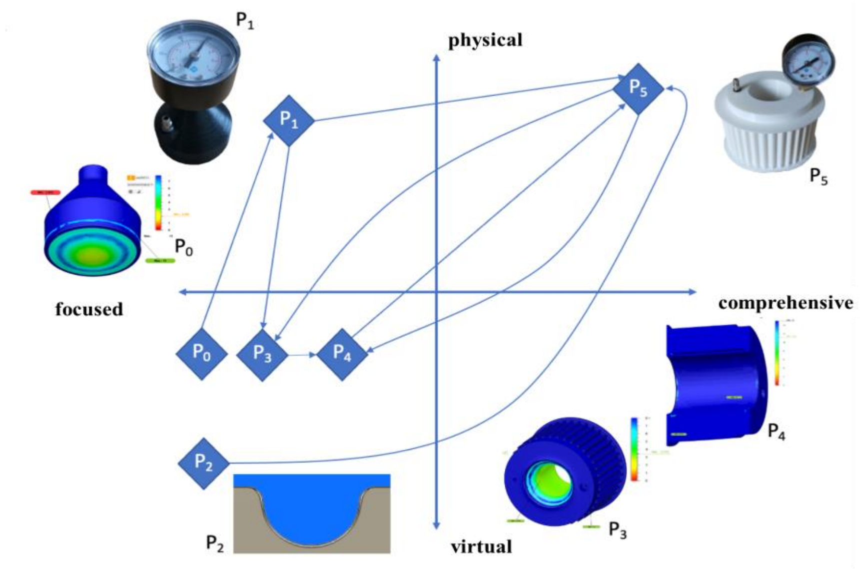

Figure 7. The dimensionality of the prototypes and the positioning of the prototyping sequence

The knowledge gained is incorporated into the next prototype P3. Although this is still in the virtual world, it is already further along the "comprehensive" axis, as several partial aspects are taken into account. The clamping machine element is simulated with an operating pressure of 12 bar. Furthermore, the wall thickness of the inner side is varied, which forms the force fit during operation through elastic deformation.

The next virtual prototype P4 is even more comprehensive. The timing belt pulley is simulated under operating conditions. In this case with hydraulic tensioning and an applied torque of 75 Nm.

5.3. Findings from the implementation phase

The implementation of the sequence planned in section 5.1.2 has shown that the combined approach is suitable for structuring the prototyping procedure at a system level. The criticality analysis of the functions was essential here. It made it possible to prioritize questions to be validated and also to group the less critical functionalities into combined issues. The highest prioritized issue in this case was the suitability of the AM process and the associated material. The prototypes produced here were exploratory in nature but very focused. It was noticeable that although the question to be answered was clearly outlined, the prediction of the number of iterations was fuzzy. The interactions between the process parameters were known quantitatively through research, but only during the prototyping activity did it become clear how many iterations would be necessary to qualify the required correlations. It would therefore be helpful for the planning to define a termination criterion for the respective activity, which initiates the next prototyping phase. What was missing here was an argument as to how gates could be derived from the requirements. In this phase, planning or support tools known from the literature (Hansen *et al.*, 2020; Lauff *et al.*, 2019; Menold *et al.*, 2017) could be used for the implementation of concrete individual prototypes.

The next prototyping activities were still very focused but were already running in parallel and in some cases looked at several functional areas in a joint prototype. This was the phase with the combined planning approach. The segmentation of the system was based on the criticality assessment. It should be examined here whether an interaction matrix might be helpful for merging the functional areas into prototypes. As the complexity of the systems increases, the designer would also have to use supporting tools for the criticality assessment.

Furthermore, it became apparent that all evaluation tasks (exploration, verification, testing) could be found in the sequence. This had not been explicitly defined beforehand but resulted from the advancing maturity level.

6. Conclusion

This paper aimed to examine procedures from product development about their suitability for planning sequences to create prototypes. Individual functionalities were to be validated for a new development using prototypes.

Classic procedures as described in Pahl and Beitz (Bender and Gericke, 2020) were examined. On the one hand, the stepwise, process-oriented approach and, on the other hand, the partial problem-oriented approach.

The advantages and disadvantages of both approaches were discussed (2.1.3) and a combined approach was proposed (5.1.2), which attempts to utilize the advantages of both methods. The combined approach is based on a fundamental problem-oriented approach. This means that the functional areas are isolated and brought to a high level of maturity one after the other. This sequence made it necessary to prioritize the functional areas. A multidimensional criticality assessment was used to achieve this, taking into account the interactions and the expected difficulties in implementation, the level of knowledge regarding the sub-problems and the importance in the product.

In the combined approach, the functional areas with the highest criticality rating were considered first and validated using planned prototypes. The other functional areas with a lower criticality rating were combined to exploit the advantages of a stepwise process-oriented approach. The validation of several functional areas was merged into one prototype. A time saving could thus be realized. This was possible because there were only a few known interactions between these areas. Finally, all solutions for the functional areas were combined and the prototype was utilized for testing.

In both sections, both virtual and physical prototypes were used for evaluation (see Figure 6).

The combined approach proved helpful in the planning of the hydraulically clampable machine element. By sequencing the prototyping activity, the increments were planned precisely and the number of validation steps was reduced. By prioritizing the critical partial functions, the properties of the associated solution were defined first. As soon as a satisfactory level of maturity was reached, several sub-areas could be merged.

Criticality assessment plays an important role in this approach. The complexity of the evaluation increases with the complexity of the system and the number of functions. The designer can be supported in the evaluation by various tools. For example, the significance in the product can be supported with the help of an FMEA and the risk priority number and interactions in the system can be mapped using a DSM. The suitability of the tools must be examined. Other metrics for prioritization are also conceivable.

In the approach presented, a moderately complex system was considered. The planning of prototyping activities is not yet very detailed with regard to individual prototypes. However, the question arises as to whether this planning approach can provide added value in the estimation of prototyping efforts, especially in the exploratory phase for the comparison of early concepts.

Furthermore, detailed planning is only possible up to a certain depth. Any subsequent cascades are of course dependent on the knowledge gained during the sequence and are susceptible to uncertainties ("unknown unknowns" Sutcliffe and Sawyer, 2013). However, the combined prototyping sequence is flexible and enables the integration of additional iterations. Both within and between the prototypes.

References

Albers, A., Klingler, S. and Wagner, D. (2014), “Prioritization of validation activities in product development processes”, Proceedings of International Design Conference, DESIGN, Vol. 2014-Janua, pp. 81–90.

Bender, B. and Gericke, K. (Eds.). (2020), Pahl/Beitz Konstruktionslehre - Methoden Und Anwendung Erfolgreicher Produktentwicklung, 9. Auflage., Springer Vieweg.

Butzke, J. (2019), Verfahrenstechnische Weiterentwicklung Des Fused Layer Manufacturing Zur Reduzierung Der Anisotropie Im Bauteil, https://doi.org/10.14279/depositonce-7651.

Camburn, B., Dunlap, B., Gurjar, T., Hamon, C., Green, M., Jensen, D., Crawford, R., et al. (2015), “A Systematic Method for Design Prototyping”, Journal of Mechanical Design, Transactions of the ASME, Vol. 137 No. 8, https://dx.doi.org/10.1115/1.4030331.

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., et al. (2017), “Design prototyping methods: State of the art in strategies, techniques, and guidelines”, Design Science, Vol. 3 No. Schrage 1993, pp. 1–33, https://dx.doi.org/10.1017/dsj.2017.10.

Christie, E.J., Jensen, D.D., Buckley, R.T., Menefee, D.A., Ziegler, K.K., Wood, K.L. and Crawford, R.H. (2012), “Prototyping strategies: Literature review and identification of critical variables”, ASEE Annual Conference and Exposition, Conference Proceedings, No. November 2018, https://dx.doi.org/10.18260/1-2--21848.

Dunlap, B.U., Hamon, C.L., Camburn, B.A., Crawford, R.H., Jensen, D.D., Green, M.G., Otto, K., et al. (2014), “Heuristics-based prototyping strategy formation: Development and testing of a new prototyping planning tool”, ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), Vol. 11 No. November 2018, https://dx.doi.org/10.1115/IMECE2014-39959.

Fricke, G. (1993), “Konstruieren als flexiber Problemlöseprozess: empirische untersuchung über erfolgreiche Strategien und methodische Vorgehensweisen beim Konstruieren”, VDI-Verlag, Düsseldorf.

Hansen, C.A., Jensen, L.S., Özkil, A.G. and Martins Pacheco, N.M. (2020), “FOSTERING PROTOTYPING MINDSETS in NOVICE DESIGNERS with the PROTOTYPING PLANNER”, Proceedings of the Design Society: DESIGN Conference, Vol. 1, pp. 1725–1734, https://dx.doi.org/10.1017/dsd.2020.132.

Hansen, C.A. and Özkil, A.G. (2020), “From Idea to Production: A Retrospective and Longitudinal Case Study of Prototypes and Prototyping Strategies”, Journal of Mechanical Design, Vol. 142 No. 3, https://dx.doi.org/10.1115/1.4045385.

Lauff, C., Menold, J. and Wood, K.L. (2019), “Prototyping canvas: Design tool for planning purposeful prototypes”, Proceedings of the International Conference on Engineering Design, ICED, Vol. 2019-Augus No. August, pp. 1563–1572, https://dx.doi.org/10.1017/dsi.2019.162.

Menold, J., Jablokow, K. and Simpson, T. (2017), “Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design”, Design Studies, Vol. 50, https://dx.doi.org/10.1016/j.destud.2017.03.001.

Schork, S., Güttinger, K. and Kirchner, E. (2020), “Analysis of properties for the development of additively manufactured prototypes—the House of Properties”, Forschung Im Ingenieurwesen/Engineering Research, Vol. 84 No. 4, pp. 293–303, https://dx.doi.org/10.1007/s10010-020-00412-3.

Sutcliffe, A. and Sawyer, P. (2013), “Requirements elicitation: Towards the unknown unknowns”, 2013 21st IEEE International Requirements Engineering Conference (RE), IEEE, pp. 92–104, https://dx.doi.org/10.1109/RE.2013.6636709.

Ulrich, K.T. and Eppinger, S.D. (2012), Product Design and Development Product Design and Development, The McGraw-Hill Companies, Vol. 5th, https://dx.doi.org/10.1016/B978-0-7506-8985-4.00002-4.