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A Method for Additive Tooling in Integrated Product Development

Steffen Schrock[1,2], Stefan Junk[1], Albert Albers[2]

[1]Hochschule Offenburg, Labor Rapid Prototyping
Badstraße 24, 77652 Offenburg, Germany
steffen.schrock@hs-offenburg.de, stefan.junk@hs-offenburg.de
[2]KIT - Karlsruhe Institute of Technology, IPEK - Institute of Product Engineering,
Kaiserstr. 10, 76131 Karlsruhe, Germany
steffen.schrock@partner.kit.edu, albert.albers@kit.edu

Abstract

In the context of successful product development, continuous validation plays a central role in matching customer requirements and product characteristics. However, the early phase of product development in particular is characterised by special challenges, which are due to a high degree of uncertainty and a lack of resources, such as a lack of prototypes. Additive Tooling (AT) offers a quick and cost-effective way of producing injection moulded products and high fidelity prototypes using the injection moulding process and provides a promising approach for addressing these challenges. Furthermore, it allows different product variants to be tested early in the development process, thus generating meaningful insights into product properties and the necessary production system. As part of the validation process, AT is embedded into a complex process environment. In many cases, the use of AT in product development practice is not target-oriented as it also lacks methodological support.

This paper presents a method for supporting the application of AT-based validation environments in integrated product development. Based on a case study, relevant process steps, activities and possible barriers in the realisation of an injection-moulded product are identified and analysed. The practical example essentially shows the need for verification of the AT application. Based on the identified requirements and sub-activities, a systematic for Additive Tooling is then derived and described. The aim of the AT-systematic is to support the target-oriented application of Additive Tooling to obtain physical prototypes at an early stage and to shorten validation cycles. Finally, it is shown how the AT-systematic is located in the integrated Product engineering Model (iPeM).

Keywords: Additive Tooling, Injection Moulding, Integrated product development, Validation and Verification, Product-Production-CoDesign

1 Introduction

Integrated product development includes all steps from the identification of market needs and the generation of ideas to the production release of a product or the market launch of a service. The goals of shortening the time from the identification of customer and market needs to the release of the product for production, the best possible fulfilment of requirements, the reduction of product development costs and improvement of the product are the focus here. To achieve this, all areas involved in the creation of a product are integrated into the product development process (Vajna & Burchardt, 2014). Validation contributes significantly to gaining knowledge and thus to successful product development. At the same time, however, it is also the most demanding and time-consuming activity in the entire product development process. Thus, validation is of central importance for further improvement in the product development process. To ensure that the product can be successful on the market later on, the validation must be carried out from the beginning and continuously during the entire development process (Albert Albers, Behrendt, Klingler, & Matros, 2016). One of the constraints of the early phase of product development that complicates validation is the lack of physical prototypes (Albert Albers, Rapp, Birk, & Bursac). Especially in the development of injection-moulded products, the early phase is characterised by poor availability of prototypes. As several adjustments to the injection moulding tool are often necessary during the product development process, this leads to an additional increase in development costs and a prolonged time-to-market (Gebhardt, Kessler, & Thurn, 2019). In injection moulding, the development of the product and the production system are highly interdependent. The term Product-Production-CoDesign (PPCD) is understood to mean the iterative planning, development and realisation of products and the associated production system through to the production, the development of associated business models and the systematic decommissioning of products and production systems. As a result, not only the planning over several product generations, but also of the corresponding production systems is taken into account (Albert Albers et al., 2022). Thus, the validation of the products as well as of the production system becomes necessary.

Usually injection moulds are produced by subtractive process. Today, Additive Manufacturing (AM) has also emerged as a possible alternative for the production of these moulds. Additive Tooling (AT) offers a fast and cost-effective way to produce near-series prototypes using injection moulding (A. Kampker, J. Triebs, B. Alves, S. Kawollek, & P. Ayvaz, 2018; Feldhusen & Grote, 2013; Gebhardt, 2016; Schrock, Fang-Wei, Junk, & Albers, 2020). Use of AT, yet, is challenged by a new process flow and a lack of application and design knowledge (Gebhardt, Kessler, & Schwarz, 2019; Kampker, Alves, & Ayvaz, 2020; Nagahanumaiah, Subburaj, & Ravi, 2008). In Additive Tooling of injection moulds, the requirements for the injection moulding and AM process must be considered simultaneously (Gebhardt, Kessler, & Schwarz, 2019; Mitterlehner, 2020). In addition, the design of the product already sets requirements for the injection mould and the injection moulding process, which makes it necessary to consider the entire development process.

This leads to the following research questions (RQ):

- RQ1: Which process steps must be considered within an integrated product development process to enable a systematic application of Additive Tooling (AT) for validation and verification?
- RQ2: How can a systematic approach be designed to generate validatable prototypes of injection-moulded products using Additive Tooling (AT) in integrated product development?

2 State of the Art

2.1 The integrated Product engineering Model (iPeM)

Based on the general systems theory, Ropohl describes product development as the transformation of an initially vague system of objectives into a system of objects by using an operation system (Ropohl, 2009). The integrated Product engineering Model (iPeM) is based on this system triple of product engineering. As a generic meta-model, which contains the relevant elements to derive situation-specific product development process models, the iPeM describes product engineering as a continuous interaction of the system of objectives, the system of objects and the operation system. The system of objectives comprises all explicit goals of a product to be developed, including their dependencies and boundary conditions. At the end of the development process, the system of objects corresponds to the product. As a socio-technical system consisting of structured activities, methods and processes together with the resources required for the realisation, the operational system carries out this transformation. Different areas of a company or a project can be represented in multiple layers. These layers are the product generations itself, the validation system, the production system as well as the corporate strategy (Albert Albers, Reiss, Bursac, & Richter, 2016).

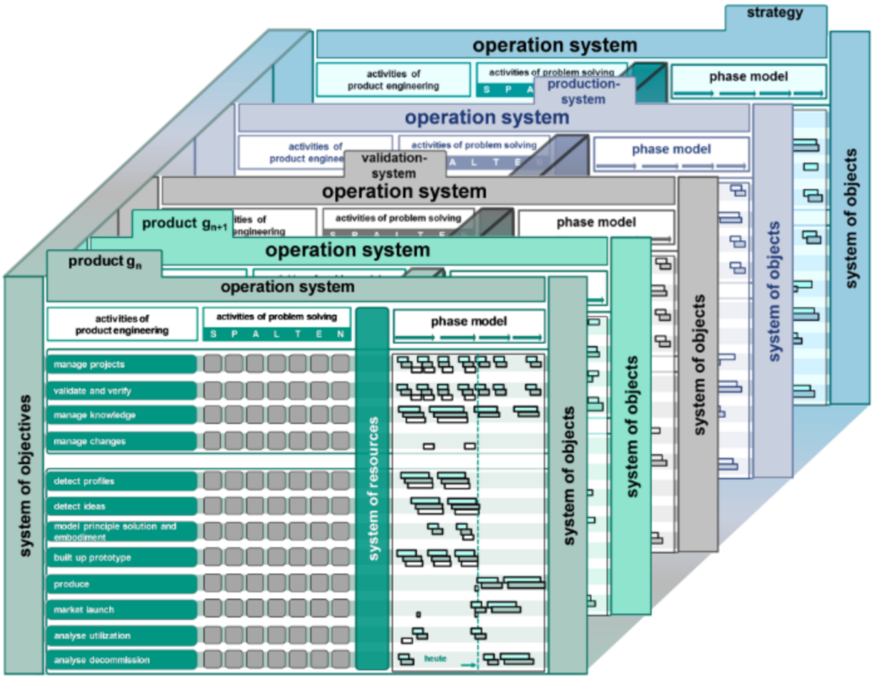

Figure 1. The integrated Product engineering Model (iPeM) in context of the product generation engineering (Albert Albers, Reiss, et al., 2016).

2.2 Additive Tooling for Injection Moulding

Additive Tooling (AT) describes an application segment of Additive Manufacturing (AM) in which a fast production of tools or moulds takes place (Gebhardt, 2016). In contrast to conventional tooling, with additive tooling the tool is built up layer by layer, which makes it possible to realise complex geometries. Common additive processes for manufacturing mould inserts are based on the principle of photopolymerisation (Figure 2) (Schuh et al. 2020; A. Kampker et al. 2018). These offer good surface quality and manufacturing accuracy for additive processes (Burggräf et al. 2022; Zhang et al. 2018; Mendible et al. 2017). In general, there is a clear difference in the technical properties of the moulds, which makes it necessary to adapt the overall process and certain process parameters (Schrock, Proksch, Rapp, Junk, & Albers, 2021). For example, the use of the AT mould inserts leads to an extended cycle time in the injection moulding process due to the poor thermal conductivity. An investigation of different mould inserts showed the increase in cycle time from 30 seconds to between 70 and 180 seconds compared to steel mould inserts (Kampker et al., 2020).

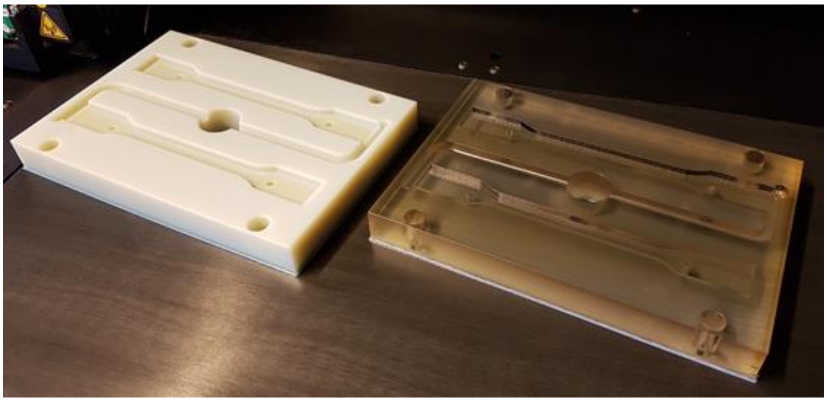

Figure 2. Additive Tooling mould inserts manufactured by PolyJet process with different materials.

Due to lower costs in some cases but a limited lifetime, AT moulds are particularly suitable for very small or prototype series. Process comparisons between additive and conventional tool manufacturing show in particular an advantage in the procurement time of AT moulds. However, the price depends strongly on the size and complexity of the mould or mould inserts (Schrock et al., 2020). Depending on various process parameters, production output in the two- to three-digit range can usually be achieved (Kampker, Triebs, Kawollek, & Ayvaz, 2018; Schuh, Bergweiler, Lukas, & Abrams, 2020). Due to the prompt availability and usually simpler realisability, possible solutions can be tried out more quickly. This serves the goal of rapid failure and the resulting early gain in knowledge. In addition to gaining knowledge about the product, knowledge about the associated production system can also be generated. A survey among experts in the development of injection moulded products and moulds revealed a need for support in technology selection and feasibility assessment, in the design and manufacture of AT moulds and in their application in injection moulding (Schrock et al., 2021).

3 Methods

In order to answer RQ1 and to be capable of mapping an AT process that is as complete and continuous as possible, a case study was carried out on the production of tensile specimens using AT (Table 1). The aim of the case study was to gain a good understanding of Additive Tooling and to build up process knowledge. This included the identification of necessary activities and process steps. To classify the identified activities in the context of integrated product development, they are then assigned to the corresponding layers of the iPeM, which are later modelled in an exemplary reference process in the phase model.

Table 1. Parameters for the Additive Tooling (AT) and Injection Moulding (IM) process

AT-Parameters		IM-Parameters	
3D-Printer	J750 (Stratasys)	Material	Polypropylene (PP)
Material	Digital ABS (RGD515+531)	Clamping force	250 kN (max.)
Print mode	High Quality	Injection temp.	220°C
Surface mode	Glossy	Injection speed	10 cm³/s
		Cycle Time	236,7 s

To answer RQ2, a proposal for a systematic application of AT is derived based on the results of the case study, which can be used in the existing iPeM model. Previous studies consisting of literature analyses, interviews and market studies were also included in the modelling of the AT-systematic (Schrock et al. 2020; Schrock et al. 2021).

4 Results

The case study is divided into two iterations. In the first run, a mould insert for Additive Manufacturing was derived on the basis of existing CAD data of a tensile specimen. It was designed in such a way that it could be used in an existing master tool, which means that some restrictions had already been set. After Additive Manufacturing, the mould insert was tested on the injection moulding machine. However, the mould insert was already so severely damaged during the sampling process that it was not possible to produce tensile specimens that could be validated (Figure 3).

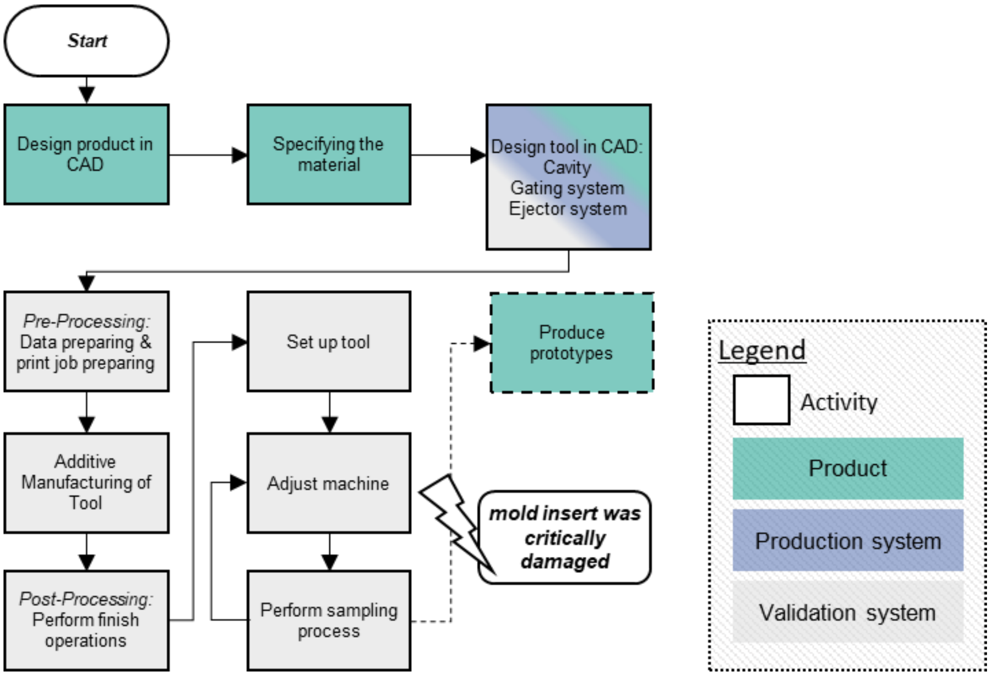

Figure 3. Retrospectively summarized flow chart of the initial test run.

The damage occurred in a relatively thin edge area of the mould insert. A subsequent structural-mechanical simulation shows that this area could have been identified as critical in advance (Figure 4). For this purpose, the mould insert was loaded with the clamping force of 250 kN at the contact surfaces of both mould halves.

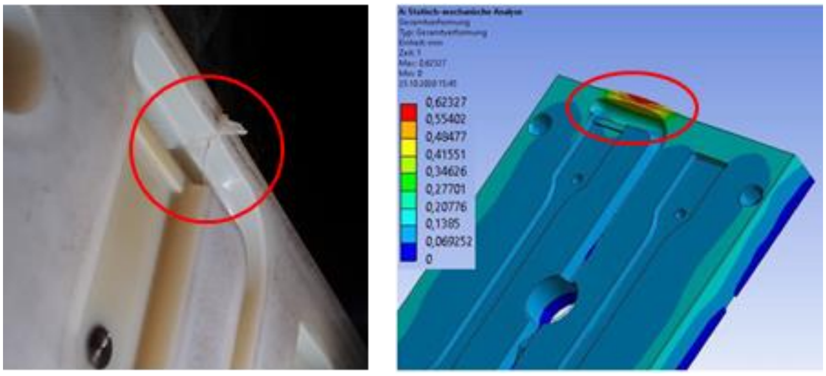

Figure 4. Damaged mould insert (left) and failure prediction by structural-mechanical simulation (right).

In addition to the first practical application findings, this trial also provided the essential insight that when using "soft" polymer moulds, an initial estimation of the mould load by means of a simulation provides important information for the mould design. Furthermore, this example clearly shows the strong link between product and production system (Figure 5). The product and its requirements largely determined the process parameters to be set in the production system. The chosen mould design could not fulfil these requirements because the size of the mould insert was limited. This triggered a revision of the product and again a re-design of the mould.

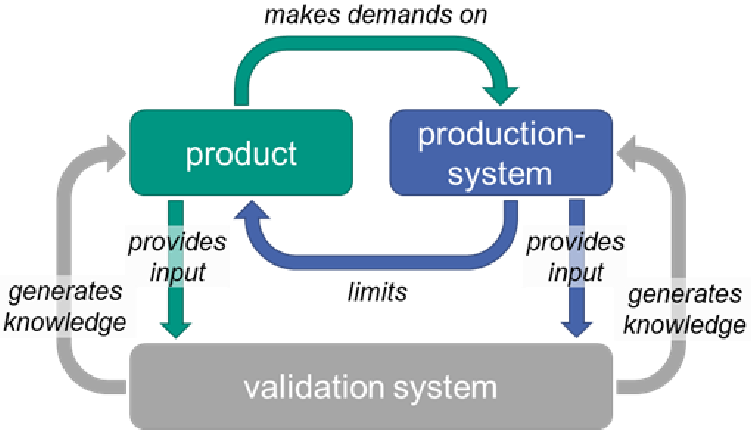

Figure 5. Interaction of the iPeM-layers in the development process.

Following the simulation, the component "tensile specimen" was revised and the mould insert was adapted. In the second run, 80 prototypes were produced with the revised mould. Only minimal signs of wear became apparent, so that further use would be possible. Due to the long cycle time of about four minutes per part, the test was terminated at this point. Figure 6 shows essential process steps from the optimised process for manufacturing the prototypes:

1) Design product
2) Design tool
3) Simulate filling study
4) Simulate structural mechanics
5) Additive manufacturing
6) Post-Processing
7) Set up tool
8) Produce prototypes by injection moulding

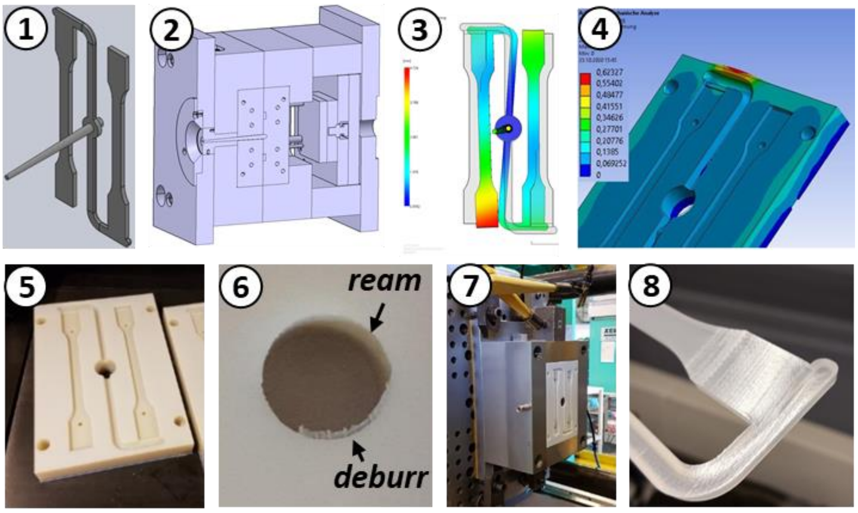

Figure 6. Summary of sub-process steps from the AT case study.

The experiences of the case study make it clear how important it is to test the suitability of the AT application. The structural-mechanical simulation allowed weak spots to be identified and potential for optimisation in the design of the mould inserts to be exploited. Required process parameters could already be determined from a simulated filling study based on the product CAD data.

This resulted in the following optimised process with assignment of the activities to the layers of the iPeM (Figure 7):

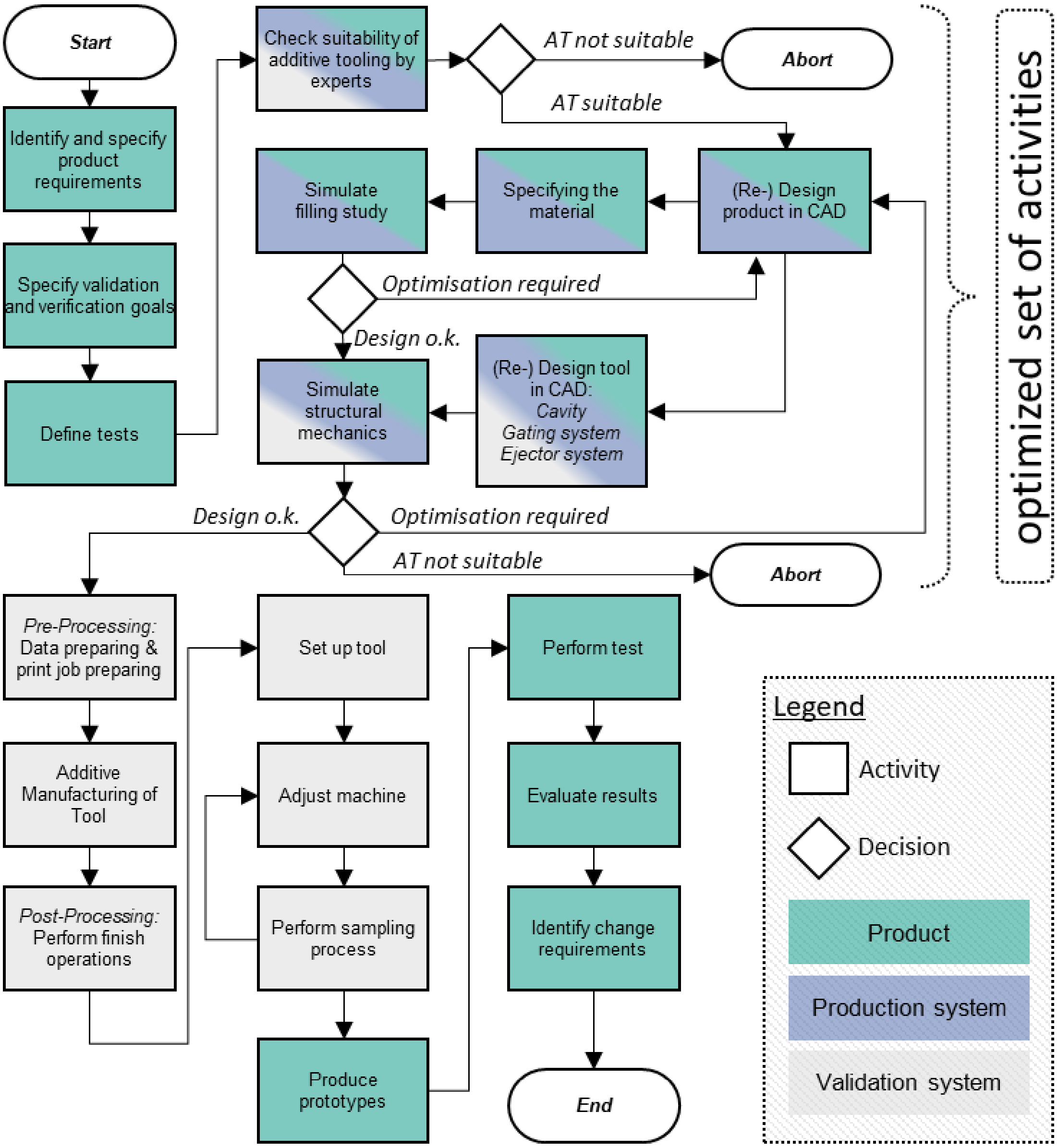

Figure 7. Optimized flow-chart of cross-layer activities from the case study.

4.1 Development of the AT-systematic

The aim of the AT-systematic is to provide the user with a user-oriented process for faster prototype production and thus earlier validation and verification of product properties. According to the core statements from expert interviews in a former work (Schrock et al. 2021), the systematic to be developed should be designed for the production of prototypes in B-sample quality (in the identical manufacturing technology and material of series production). An existing product profile with customer requirements and existing product CAD data are assumed because these would already be necessary in the A-sample phase (manufacturing technology and material deviating from series production, e.g. 3D-printing).
The activities identified in the case study are allocated to six process phases. Within a phase, activities can be carried out according to the established problem-solving process "SPALTEN" (German acronym for "to split"), which is a cycle of problem-solving activities in a specific

sequence: situation analysis (S), problem containment (P), detection of alternative solutions (A), selection of solutions (L), analysis of consequences (T), deciding and implementing (E) and recapitulation and learning (N) (A. Albers, Burkardt, Meboldt, & Saak, 2005). In addition, a main output is defined for each phase, which should be delivered before the start of the next phase (Figure 8).

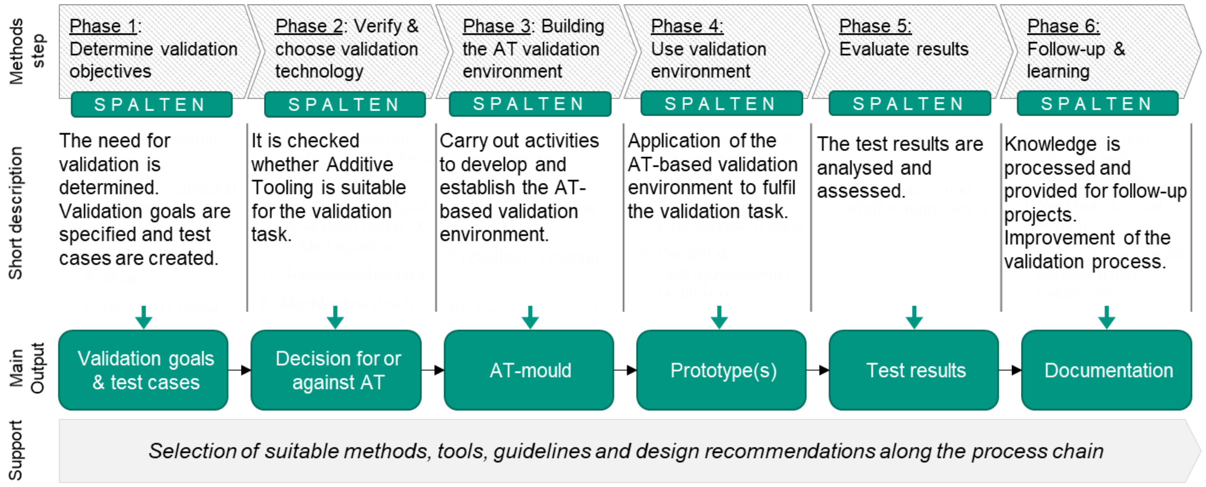

Figure 8. AT-systematic with the six phases for developing and using of an AT-based validation environment.

The individual phases are described in more detail below:

Phase 1: Determine validation objectives

The demand for validation and verification is determined.

To analyse the initial situation, the completeness of the requirements profile for the product should be checked and, if necessary, supplemented. According to the requirements, the product or production system properties to be validated and verified are then specified and transferred into validation or verification objectives. To fulfil the objectives, test cases are defined which contain specified requirements for the prototype. The validation objectives are determined in the “product” or “production system” layer, depending on which system is to be validated.

Phase 2: Verify & choose validation technology

It is checked whether Additive Tooling is suitable for the validation task.

For each validation or verification objective, it is assessed which technology enables adequate fulfilment of the validation or verification task. For this purpose, requirements for the prototype(s) must be defined and compared with the possibilities of AT, as well as various other prototyping technologies (e.g. XR/VR, simulation, 3D printing). If necessary, different types of prototypes are needed, which are realised by different prototyping technologies. If possible, different validation and verification tasks can be tested with the same prototype and thus be combined.

A team of experts with appropriate experience in the respective technology should be consulted for the selection. If mould CAD data are already available, a structural-mechanical simulation of the mould (or mould insert) can provide an estimation of whether it can withstand the expected loads. In this way, the validation system can be validated. It should be noted that in case of failure of the AT tool, conventional manufacturing might have been cheaper and faster. A trade-off should be made between the benefits and expense of tool simulation and the trial-and-error approach.

The selection and testing of the validation environment takes place in the “validation system” layer. However, knowledge from the layers “product” and “production system” is required. In some cases, this knowledge or necessary resources are only obtained during *phase 3*, which is why an iterative approach should be used here if necessary. At the end of the phase, there are defined test cases with the prototyping technologies defined for them.

Phase 3: Building the AT-based validation environment

Carry out activities to develop and establish the AT-based validation environment.

In order to set up an AT-based validation environment, specific aspects have to be taken into account. These include, for example, the technical properties of AT tools due to the AM-material and the associated restrictions in the design and use of these tools. In the tool design, for instance, attention should be paid to sufficiently large wall thicknesses and draft angles. It should also be noted that the moulds produced by an AM process often require further finishing steps (e.g. deburring, reaming of ejector holes, etc.). On the part of the injection moulding process, among other things, the clamping force, the injection and holding pressure, as well as the thermal load on the AT moulds should be taken into account. The set-up of the validation environment takes place in particular in the layer "validation system" in the activities "model principle solution and embodiment" and "produce". After the validation environment has been set up, it is available to the “product” and “production system” layer.

Phase 4: Use validation environment

Application of the AT-based validation environment to fulfil the validation task.

The use of the validation environment usually begins with the set-up and adjustment of the injection moulding machine, which is accompanied by a sampling process. In our own tests, a procedure that has proven successful is to start with a low filling volume and low clamping force. The temperature of the AT mould inserts should also be kept as constantly low as possible (e.g. cooling with compressed air). As soon as a sufficient quality of the moulded parts is achieved, the prototypes that are to be tested are produced. Afterwards, the tests defined in the validation or verification task are carried out. The use of the validation environment is carried out in the activities “build prototype” and “validate and verify” in the “product” or “production system” layer.

Phase 5: Evaluate results

The test results are analysed and assessed.

When evaluating the test results, the manufacturing boundary conditions on which the prototype production is based must be taken into account. Manufacturing or process parameters that deviate from the later series production process can lead to deviating properties between the prototype and the product. A potential discrepancy should already have been taken into account in *phase 2* “verify & choose validation technology”. This phase mainly takes place in the "product" or "production system" layer, depending on which is to be validated. However, it also requires knowledge from the other associated layers.

Phase 6: Follow-up & learning

Knowledge is processed and made available for follow-up projects.

The continuous documentation of all activities and associated processes is finalised and reflected. If necessary, the process model can and should be adapted for subsequent validation & verification activities. This takes place across all layers.

4.2 Additive Tooling in the phase model of the iPeM

To create a description model of the AT-systematic within the iPeM, the following relationships are defined: As already stated, the product sets requirements to the production system - the production system limits possible characteristics of the product through manufacturing restrictions. The development of an AT-based validation environment is seen as an individual process, which is closely linked to the development of the product and the production system. The development of the validation environment takes place in the separate layer "validation system". The objects created in the validation system (such as the AT-tools) are available to the corresponding activities in the development process via the common system of resources. Required resources of the production system are available to the validation system via the resource system and vice versa.

The activities described in the phases of the AT-systematic represent sub-activities of the basic and core activities described in the iPeM and are illustrated exemplarily and simplified in the phase model of the iPeM (Figure 9) using the activities from the presented case study as a base:

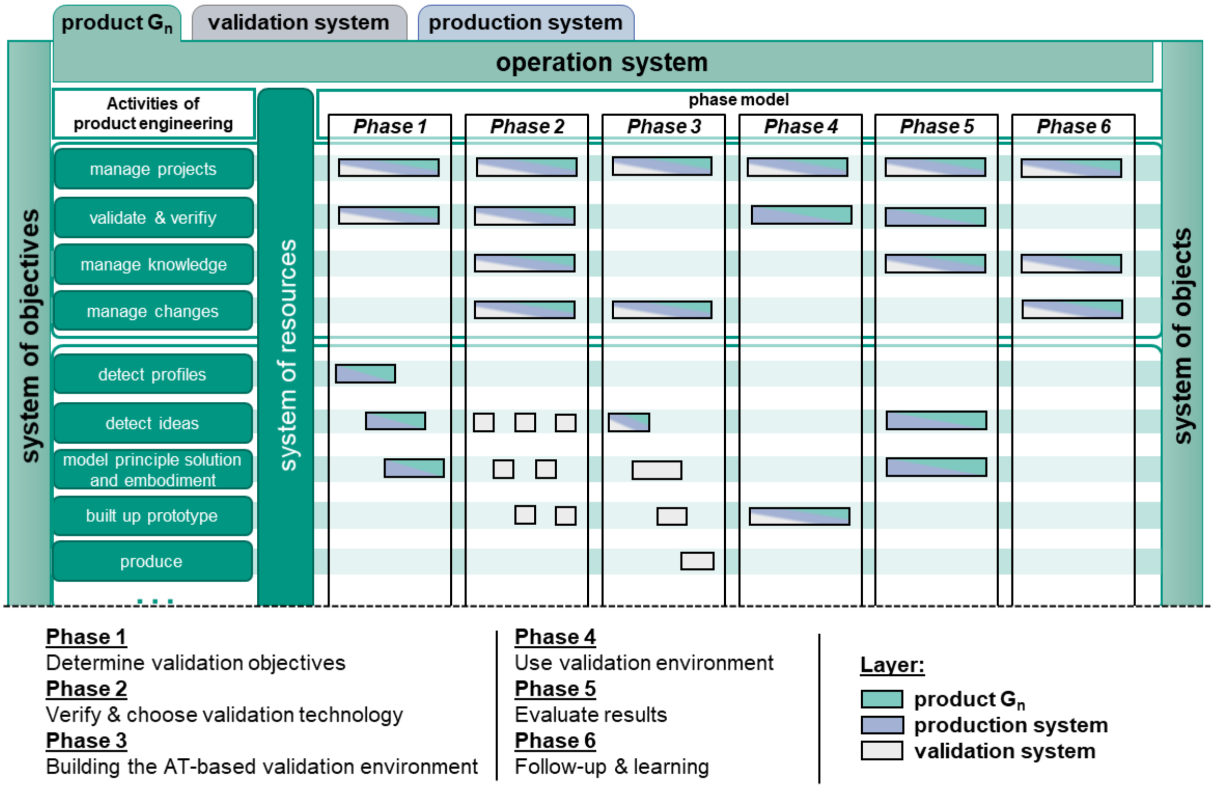

Figure 9. Cross-layer representation of exemplary activities of the AT case study in the phase model of the iPeM.

5 Conclusion and Outlook

Additive Tooling has great potential for early prototyping and for supporting validation in product production co-design, as was seen from the literature review and the case study conducted. This work contributes to the use of an AT-based validation environment within integrated product development by providing a systematic procedure model containing the main steps for the development and use of AT-moulds. For this purpose, necessary process steps and activities were first identified, responding to RQ1. These were transferred into a systematic, which is intended to support from the determination of the validation requirements to the interpretation of the results, giving an answer to RQ2. The investigations show how important the suitability test respectively the validation of the AT-based validation system is in this context. In the future, the developed approach will be supplemented by a design and application guide, which also will provide established and supporting methods. It is to be expected that the fidelity, which can be achieved through AT-prototypes, will improve in the future because of technical advances in AM-technology and AM-material.

The methodological support is actually under evaluation in two case studies. The first one in a students’ workshop in a practical development project. The second study is taking place within a research project in cooperation with an industrial company. Therefore, a development task is given to a development team in which AT-prototypes are to be generated using the AT-systematic.

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