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VALIDATION CONCEPT FOR THE INVESTIGATION OF EFFECTS OF MODULAR PRODUCT FAMILIES

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Abstract

In order to meet an increasing internal variety, a solution can be the modularization of products. To motivate modularization projects throughout all phases of life, different effects of modular product families were collected in previous works on a literature basis. In this paper, a validation concept is presented, which will investigate these effects by using statements directly from industry representatives. In particular, the industry background is included in the evaluation to generate a more differentiated overall picture of impacts of modular product families.

Keywords: modularisation, design knowledge, empirical studies, effects of modularisation, boundary conditions

1. Introduction

To be able to fulfil more and more different customer needs, companies are challenged to offer an increasing number of product variants (Krause and Gebhardt, 2018). This has different effects in all product life phases: The companies need more development time, the database-management is getting more complicated, the stock costs increase because different product variants have to be stored, and so on (Abdelkafi, 2008; Perera et al., 1999; Gebhardt et al., 2016).

An option to handle these problems is to change the product architecture into a more modularised one, which is having a lot of positive effects, for example there are fewer variant components, postponement in production is possible and the option to configure to order is given (Krause and Gebhardt, 2018). These and a lot more effects were recorded literature-based in previous works and stored in a consolidated impact model of modular product structures (Hack and Krause, 2017). In this paper a concept is presented to validate the contents of the impact model. The validation concept was developed in order to be able to query some company boundary conditions on the one hand and the effects of modularisation on the other in a structured manner. The validation of the effects is carried out with several industry representatives with different company backgrounds, with the aim of linking the company conditions to their experience on the effects.

The impact model of modular product structures (Section 2) is used to derive requirements for the study design of the validation concept (Section 3.1). The resulting two-stage validation concept consists of an online-survey and expert interviews (Section 3.2). Section 4 presents the results of the survey, which are further elaborated with the statements made in the interviews. A discussion and an outlook conclude the paper.

2. Impact model of modular product structures

The modularisation of product structures results in different effects and consequences for companies in the entire product development process. There are a lot of effects of modular product structures already described in the literature, e.g. in the form of individual impact models of several case studies (Harland and Uddin, 2014), in literature studies (Boer, 2014; Chiu and Okudan, 2014) or in the formulated objectives of method documentations (Pakkanen et al., 2016).

Hackl and Krause compiled the effects in several papers (Hackl and Krause, 2016, 2017; Hackl et al., 2019). The Effects are transferred into a literature-based consolidated impact model of modular product structures (short: impact model). It is a model which shows qualitative correlations between changes in modular product structures and their effects in different life phases. The impact model represents qualitative and causal relationships which have been compiled from different literature sources (Hackl and Krause, 2016). Initial findings show that a model like this is desired in industry to motivate modularisation projects across life phases.

The modular product structure is described within the model with the characteristics of modularity, such as commonality or combinability. Commonality means that one module or component is used in different product variants in a product family. Commonality is made possible by oversizing and interface standardization. The interface standardization, decoupling of modules and the function binding, which means that individual modules fulfil individual functions, enable the combinability of modules to generate new product variants (Salvador, 2007). Oversizing is a newly introduced characteristic by Hackl and Krause which describes that modules are developed in a way that they can be used for different product variants (Hackl and Krause, 2017). The different characteristics of modularity have several effects in the life phases like product development, procurement, production, sales & marketing and use & customer service. In total, Hackl and Krause have collected more than 80 effects. These effects are presented in effect chains in the impact model, which arise from the characteristics of modularity and lead to effects on economic target values. Figure 1 shows an excerpt of the impact model.

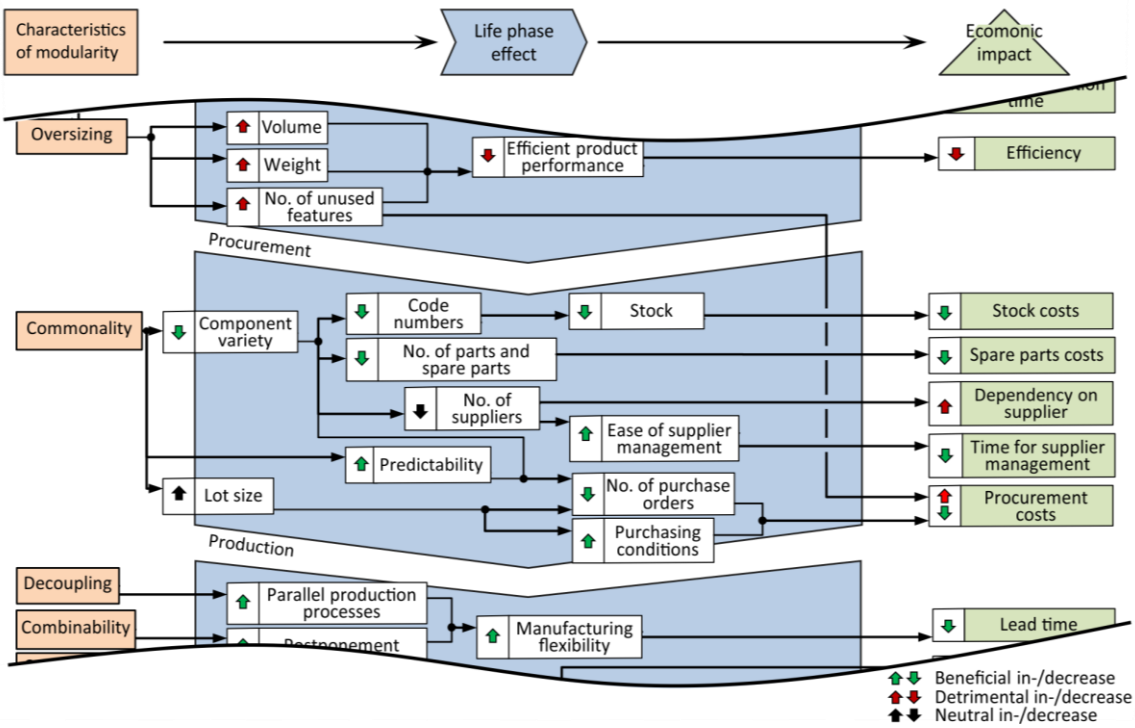

Figure 1. Excerpt of the impact model (according to Hackl et al., 2019)

Figure 1 shows effect chains resulting from the modularisation characteristics. The increase in the procurement lot size is for example achieved directly from the communal use of modules in a product family and is therefore a so-called primary effect. Two secondary effects result from the increase in lot

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size: the reduction in the number of orders and the improvement in purchasing conditions, for example through volume discounts for larger purchases from suppliers. The secondary effects lead to the economic impact of reducing procurement costs. Within the scope of this paper, the primary effects are of particular importance, as they are directly related to the modular product structures.

3. Study design for the validation concept

This section first describes requirements for the validation concept. The resulting validation concept is then presented.

3.1. Requirements for the validation concept

In order to further increase the validity of the impact model presented, it is necessary to validate the impacts on the basis of industry representatives. There are two reasons for this: Firstly, effects can be measured in case studies and secondly, the impact model should be applicable in industry.

Hackl et al. presented a pilot survey to validate the effect chains of the impact model (Hackl et al., 2019). Therein, large product family modularity projects were studied across a range of industrial firms. 9 participants from producing companies took part in the survey. The participants where given the impact model and they were supposed to pick the effect chains they could find in their case studies. With this survey, Hackl et al. found out dominant effect chains for the 9 participants in the life phases product development, procurement and production. The results of Hackl et al. (2019) give a first insight on which effect chains can appear by modularisation projects in companies.

Nevertheless, the statements of the study participants on the effects and effect chains were not related to the background of the participants. In this paper, the validation will be continued, because with a more detailed look on the experiences of people working in industry the informative value of the impact model can be strengthened. It is particularly important to increase the sample size in order to obtain more valid statements. Besides the questions on which effect chains are dominant, it is also important to know which effects or whole effect chains are maybe not detected in modularisation projects or even appear to be opposed. The profile of the study participants is also very important, as the occurrence of effects or even non-occurrence may depend on it. In addition, effects chains in the life phases use & service are relevant, since these are the effects which are not so self-evident, because it is the product development, which is often having the lead in modularisation projects.

The above-mentioned points result in several requirements for a more detailed validation concept. We want to find out, which primary effects of the impact model occur or not occur in industry and why. Since it is mainly the primary effects that need to be queried, the relationship to the characteristics of modular product structures is important. The characteristics of modularity must be explained to the interviewees in a way that is generally understandable and close to the company. Furthermore, it is interesting whether further effects occur in industrial practice that are not yet part of the impact model. In addition to the query of the primary effects, the company background should also be queried. In the evaluation, it must be possible to match given company boundary conditions of the study participants to their opinion on the primary effects, if these differ greatly.

The organisational requirements are that the validation should not be too time-consuming so that it can be carried out by industry representatives in addition to everyday business. The concept should enable a structured query, which is also reproducible. In addition, the questions should be adapted to the knowledge of the respondents, so that the respondents only receive questions that they can answer. The validation concept must make it possible to carry out a large number of surveys on the one hand and to include background information on the answers on the other if there is a need for clarification.

3.2. Survey-based interview study

The requirements lead to a survey-based interview study which is subdivided into two parts. The procedure model of the study is explained in Figure 2. The first part of the validation is conducted by an online-survey. An online survey can be easily distributed and evaluated without much effort. The second part of the validation are expert interviews with participants from the survey from validation

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part 1. If the first part is rather quick in asking many simple questions, expert interviews provide a deeper insight into modularisation projects and companies.

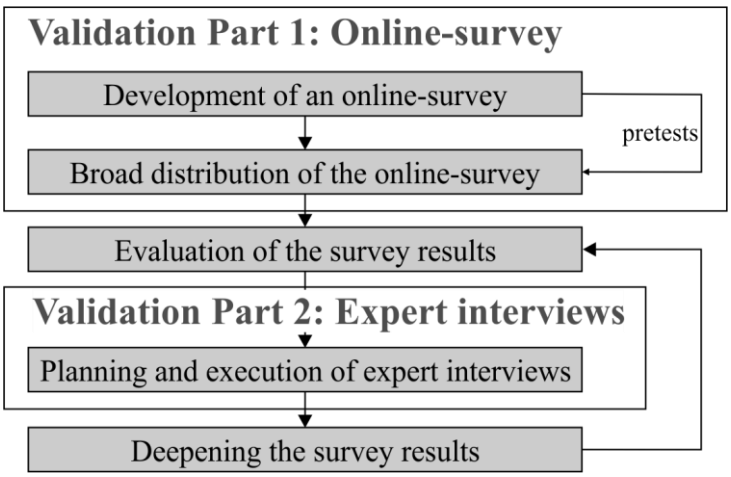

Figure 2. Procedure model of the survey-based interview study

3.2.1. Validation Part 1: Online-survey

The online-survey for the validation of the effects of the impact model is built up with the help of limesurvey®. The survey is structured in four sections: Questions about the background of the companies, questions about modularisation projects, questions about the effects of modularisation characteristics and a conclusion.

Questions about the background of the companies

On the first page, the estimated duration of the survey and an email address for questions is given. After that, questions about the companies of the participant are asked. This block of questions serves as an introduction to the survey, but is also very important for the evaluation, since certain boundary conditions that are set here may be related to the occurrence or non-occurrence of effects. Questions, which are asked here are for example the question about the position of the survey participant in its company or also the question whether the company is a producing company. If the question is answered in the affirmative, there is the optional question asked which kind of production is used, such as large-lot production, small-lot production or single-piece production. The questions in this block are closed, which means that there are predefined answer options available. Closed questions offer the great advantage that the answers obtained can be easily compared with one another and thus quickly evaluated. There is also an advantage for the persons, because closed questions are usually easier and therefore quicker to answer, since the own answer does not have to be written down in own words (Diekmann, 2018).

Questions about modularisation projects

The next block of questions introduces the topic of modularisation and poses the essential question of whether the survey participants themselves were already part of a modularisation project or whether they assisted such a project in an advisory capacity. If this question is answered with no, the survey will end here. If the answer is yes, an open question will be asked on which modularisation methods were used for the modularisation project. The survey participants shall describe in key points how they carried out the modularisation. This is an open question. Open questions are characterized by the fact that there is no predefined answer possibility. This fact corresponds to the greatest advantage of open-ended questions, since the participants are not bound to a given answer format and can therefore carry their own knowledge as an answer (Porst, 2014; Diekmann, 2018). Depending on the answers it can be seen how profound the knowledge about modularisation methods is. In addition, it is asked at which life phase the participants have experience in the context of the effects of modularisation. Here the participant can select a maximum of two life phases. This has the advantage that, on the one hand, it can be assumed that survey participants will only be asked questions that they can answer and, on the other hand, the duration of the online survey can be controlled.

Questions about the effects of modularisation characteristics

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The next question blocks are all built up in the same way and will appear one after the other. In the blocks, the opinions of the survey participants is queried to the effects which are part of the impact model of Hackl et al. (2019). As the primary effects in the impact model can be assigned to the characteristics of modular product structures, every characteristic is having its own block. On top of the blocks, the single characteristics are described. This description part stays visible the whole time while the survey participants answer the questions in the block. After the introductory explanation, the individual life phases (which are chosen before) will be gone through step by step. The questions in the question blocks are all structured according to the same scheme, which is depicted in the example in Figure 3.

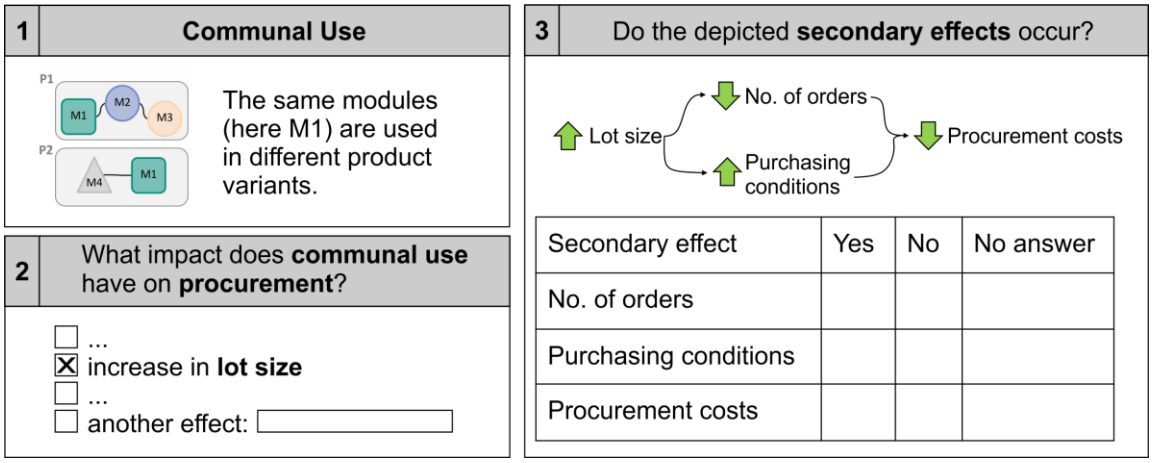

Figure 3. Schematic structure of the question blocks

In the question block of the characteristic commonality, the communal use is described in the beginning (**1**). After that, we ask the survey participants which effects, directly influenced by communal use, occurred in the life phases, in this example procurement (**2**). This question is a hybrid question. The survey participants are able to express their own opinion on a topic, even if this does not match the possible answers. This not only increases the motivation of the survey participants, but also reduces the abort rate of a survey (Porst, 2014). When a primary effect is chosen by the survey participants, an additional question shows up (**3**). It includes a picture of the effect chain of the primary effect. Since the primary effect lot size was selected in this example, the effect chain shows the secondary effects of increasing the lot size. The participant can now choose which secondary effects will occur in his or her opinion. The following answers can be given in the matrix query to the occurrence of the secondary effects: Effect does not occur; effect occurs or no response possible. There is also an "no answer" option so that participants are not tempted to guess if they cannot show a tendency to an effect.

Conclusion

The last block of questions ends the survey. The survey participants are asked if they would be available for further interviews. They were also able to ask questions and to comment on the survey itself.

3.2.2. Validation Part 2: Expert interviews

The experiences of the survey participants on the occurrence of the primary and secondary effects are surveyed in the online survey using closed questions. Respondents are able to say whether or not they thought an effect occurred, but they are unable to say why. For the 'why' systematic expert interviews should be carried out with the survey participants who agree for that in the end of the online-survey. In addition, respondents are able to substantiate the opinions expressed by providing evidence and explanations.

For the interviews, an interview guideline was developed. The objective of a guideline is to use the questions posed to generate the knowledge necessary to answer the research question or to confirm the hypotheses. The conduct of an expert interview is based on a guideline, which is defined before the interview and thus serves as methodological and content preparation. The subject area to be asked for and the interview are structured. The guideline contains pre-formulated, unclosed questions in order to give the expert the opportunity to answer freely. The interview questions are not processed chronologically, but can be asked flexibly. They serve as a support for the interviewer to define the

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knowledge framework to be asked. The selection of the expert determines the main topic, which can be asked in the interview. The guideline must be adapted to the expert on a person and function basis. The data collected with the guideline may have to be anonymised with regard to secrecy (Kühl, 2009). The guidelines for the interviews, and thus also the interviews themselves, are divided into 3 parts. The first part is the introduction to the interview, which offers the same answers on company background as in the upstream online-survey. If the interviewee did the online-survey before, this part can be shortened. After that, the interviewee is asked some introductory questions about their modularisation projects. In this context, terminologies can be discussed which are important for the interview. In addition, further questions are asked about the company background. In the second part, the individual effects, on which statements were made in the online-survey, are discussed to get a deeper inside and to understand, why which statement is given in the online-survey. The query is made chronologically according to the life phases the interviewee has chosen. If the interviewee didn't participate in the online-survey, a set of important effects will be predefined before the interview. The expert interview is concluded by the exit phase which is the third part. It does not contain any new knowledge-generating questions, but offers the possibility of final clarification of higher-level and unanswered questions. In addition, the experts can be asked whether they can be contacted again for further questions.

4. Results of the validation of selected primary effects

After a pretest, the online-survey was distributed in the industry. In total, 55 participants fully completed the online-survey. Contact data could be made available voluntarily for queries and if the survey participant was prepared for an intensive expert interview. In addition, 6 interviews with participants of the survey have already been conducted.

4.1. Pretests

For the online-survey, a pre-test was carried out with two test persons. After they had completed the pretest, feedback was collected for optimizing the survey. It emerged from the pretest, that some terms in the questions were unclear, so that they can be understood differently depending on the target person. This point of criticism is of high relevance, since an unclear wording leads to falsified answers and thus to unrepresentative results. The survey was optimised by choosing the given answer possibilities exhaustively and by simplifying and standardising the terminology. In addition, images were inserted into the survey so that the interrelationships could be better understood. The format of the survey and the duration of the survey were assessed as positive. The possibility of continuing the survey later and the omission of mandatory questions were also assessed as positive aspects on the basis of the feedback.

4.2. Participant profile of the online-survey

As the survey participants (ps) were able to select life phases, the questions of which effect occurs were asked with varying frequency. The most survey participants could make statements about the product development (37 ps). This is followed by production (14 ps), procurement (11 ps) and sales (9 ps). Only two survey participants could make statements to the use and the service.
Most of the survey participants were team members and departmental heads, followed by project managers and engineers. Other survey participants came from coaching and consulting, management or system architects. A large number of survey participants came from the plant and mechanical engineering sector (60%), followed by the aerospace industry. In addition, most of the companies surveyed were manufacturing companies (76%). Of the participants from manufacturing companies, 49% indicated large-lot production, 41% indicated small-lot production and 10% single-piece production as production type.

4.3. Evaluation of the responses to the occurrence of (primary) effects

Selected results of the validation are presented in Table 1. In the first column there are the characteristics of modularity which should trigger the primary effect according to literature. In the second column, the effects are listed with the corresponding life phase. The last two columns show the survey result.

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Table 1. Survey results on primary effects

Characteristics of mod.	Primary effects	confirmed	disproved
Interface standardisation	Simplification of reconfigurability / upgradeability (Use)	100%	0%
Combinability	Simplification of configurability (Sales)	89%	11%
Communal use	Increase in lot size (Procurement)	89%	11%
Communal use	Increase in no. of reused components (Product development)	81%	19%
Decoupling	Increase in manufacturing flexibility (Production)	79%	21%
Communal use	Decrease in component variety (Production)	69%	31%
Communal use	Decrease in component variety (Product development)	67%	33%
Communal use	Decrease in component variety (Procurement)	56%	44%
Interface standardisation	Increase in manufacturing flexibility (Production)	55%	45%
Combinability	Simplification of postponement (Production)	45%	55%
Oversizing	Increase in no. of unnecessary production steps (Production)	40%	60%
Function binding	Increase in manufacturing flexibility (Production)	20%	80%
Function binding	Enabling product imitation (Sales)	13%	88%
Oversizing	Reduction of product differentiation (Sales)	13%	88%
Decoupling	Fewer product innovations (Product development)	8%	92%

In the evaluation, the results on the primary effects were divided into three categories: predominantly confirmed effects, effects with dependency on boundary conditions and different modularisation characteristics and predominantly disproved effects.

4.3.1. Predominantly confirmed effects

In this section, effects are presented which were confirmed by more than 80% of the survey participants. Ericsson and Erixon describe that the **reconfigurability or upgradeability** of products can be strengthened by interface standardization in the life phase use (Ericsson and Erixon, 1999). This was confirmed 100% by the respondents.

Similarly, the literature also describes that the combinability of modules increases the **configurability** of products in sales (OuYang et al., 2014). This effect was confirmed by 89%. In the expert interviews, it was also stated that the configurability of modules to generate product variants leads to the fact that sales can react quickly to customer wishes.

According to Perera et al. the **lot size** should increase in the procurement by the communal use of modules in a product life phase, since more standard parts can be procured together (Perera et al., 1999). The effect lot size was affirmed to 89%, thus the statement of the industry representatives corresponds with that from the literature. Using this example, Figure 4 shows how the validation results can be integrated into the impact model.

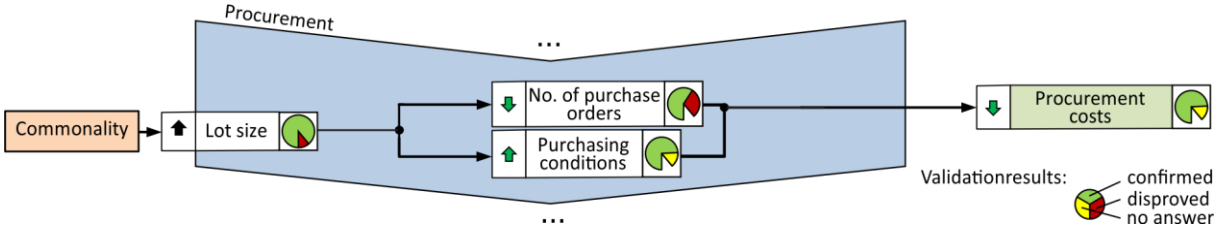

Figure 4. Integration concept of the validation results in the impact model

The incomplete circles in the secondary effects and the economic effect indicate that for these effects only those survey participants, who affirmed the primary effect, were able to respond. In literature, the increase in lot sizes has a greater influence on large-lot producers than on small-lot producers since large-lot producers are having higher numbers of orders already (Hohnen, 2014). This could not be confirmed by the survey. However, the interviewees gave initial indications that this effect depends strongly on the type of product, the purchasing strategy and the depth of production.

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The fact that the **reuse of components** in product development is to be simplified by the communal use of modules is shown by many references (Abdelkafi, 2008; Harland and Uddin, 2014; Hölttä-Otto, 2005; Robertson and Ulrich, 1998; etc.). This effect was confirmed by 81% of the survey participants. According to the interviewees, this had a positive effect on the whole development period.

4.3.2. Effects with dependency on boundary conditions and different modularisation characteristics

In this section, effects are presented that have been partly confirmed and partly denied. The effect that **postponement** is possible, which is described by Boer (2014) among others, should occur in the life phase production by increasing the combinability of modules. This effect was only confirmed by 45% in the survey. The additional consideration of the given company boundary conditions showed that this effect strongly depends on the type of production. If this information is added, it becomes clear that this effect was more likely to occur with large-lot producers (affirmed by 100% of large-lot producers) than with small-lot producers or single-piece producers (negated by 75%/100% of small-lot or single-piece producers).

According to literature, the effect that the **component variety** decreases is significant in the life phases of product development, procurement and production (Ericsson and Erixon, 1999). In the survey, the effect was similarly confirmed in all three life phases considered: 69% in production, 67% in product development and 56% in procurement. Different statements on this effect were recorded in the interviews. On the one hand, according to the interviewees, the scope must be considered. The modularisation of only one partial product family does not result in a strong reduction of the variety of components for all products as a whole. Particularly in special machine construction, there is always a need for customer-specific adaptation of the modules. As a result, the component variety has not been significantly reduced since the components differ in their geometric adaptation. Besides that, the reduction of the variety is perceived as positive, especially in the product development of large-lot producers, since the economies of scale are particularly high.

A further effect is the increase in **the number of unnecessary production steps** in production due to oversizing (Hölttä-Otto, 2005). 40% of the respondents agreed with this effect. According to the survey, this problem only occurs with the surveyed large-lot producers (confirmed by 100%) and not with the single-piece producers (confirmed by 100%). Small-lot producers agree with this effect by 25%.

The increase in **manufacturing flexibility**, which occurs in the production, is a special effect. According to the literature, the effect can occur through decoupling, interface standardization and functional binding (Jacobs et al., 2011; Ericsson and Erixon, 1999; Boer, 2014). The survey shows very different results for the three characteristics: Manufacturing flexibility through decoupling of modules was confirmed by 78%, manufacturing flexibility through interface standardization was confirmed by 54%, manufacturing flexibility through functional binding was confirmed by 20%. When asked in the expert interviews, it emerged that most interviewees do not see the connection to functional binding and that interface standardization and decoupling are usually considered together.

4.3.3. Predominantly disproved effects

Some of the effects listed in the impact model were refuted in survey by more than 80% of the survey participants. Two of the effects are listed in the life phase sales. On the one hand, the functional binding should make it possible to **enable product imitation** (Ulrich, 1994) and, on the other hand, oversizing should lead to **product differentiation** only being possible to a limited extent (Desai et al., 2001). Both effects were confirmed by only 13% of the survey participants. In the expert interviews it was said that these effects are strongly related to the complexity of the product.

Another negative effect is the risk that fewer **product innovations** could occur due to decoupling (Hölttä-Otto, 2005). This effect is the most contradicted effect in the online-survey with only 8% confirmations. The interviewees see no influence of modularisation on product innovation. They understand product innovation as a definition on the functional level, which is superior to modularisation. It was also mentioned, that close cooperation in product development can avert this risk.

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5. Discussion

The format of the online-survey and, above all, the filter options were chosen to suit this complex topic. As the survey was conducted with limesurvey®, the data could be easily evaluated. As the expert interviews were based on the online-survey, some terms were directly clear and did not have to be explained again. Before the interviews were carried out, the survey results were already evaluated. This meant that the interviewees' statements could already be evaluated in the overall context. If the interview was limited in time, the effects, where the respondent had a different experience than the average of the online survey, were directly addressed. Preliminary studies of the interview procedure resulted in an average query time per effect of 2 minutes.

A large validation was carried out for this paper. The basic question at this point is from which sample size or generally from which point the impact model can be considered validated or whether this is possible at all. Validation in industry can only provide information on the experiences of the survey participants on effects, not necessarily on effects that actually occur. By shifting the focus of validation more towards expert interviews, knowledge about the actual effects can be better captured.

During the evaluation it became obvious that the boundary conditions play an important role for the interpretation of the results, if the respondents gave answers that differed widely (see 4.3.2). In this paper, initial relationships between the effects and some company conditions are uncovered. More boundary conditions should be included in order to be able to relate them to the effects, such as organisational structure or complexity of products.

In addition, the question about the description of modularisation measures made clear that there is a wide discrepancy between the handling of the topic in industry and in research. Approximately 20 survey participants had no experience with modularisation. It would have been interesting if they could imagine to carry out modularisation and which goals they would address.

6. Conclusion and outlook

The online-survey and expert interviews show only tendencies. More expert interviews need to be conducted. In addition, more company studies should be conducted over a longer period of time in order to obtain more valid statements through better data insight. The inspection of data enables the experts' statements to be verified even better. In addition, key figures can be stored with the effects in order to describe them more precisely.

The validation generated new information on the already very extensive impact model. In order to still be able to display all information, the aim is to develop a filterable impact model. This can be done with the help of Model-Based Systems Engineering. Different views of the impact model can then be derived from a central data base. An example of this would be a model, that shows a small-series producer in particular what effects could occur if they modularized their product structures. But of course, no guarantee can be given for the occurrence of effects.

In addition, it should be possible to trace the effects back to specific modularisation methods. In this way, they could select the desired effects from the impact model. By tracing these effects back to the characteristics of modularisation and then to modularisation methods, that reinforce exactly the characteristics of modularisation, a recommendation for a modularisation method can be made.

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