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EVOLUTION OF PROPERTY PREDICTABILITY DURING CONCEPTUAL DESIGN

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Keywords: Product properties, early design phases, design models, case study

Abstract

A product is designed with the purpose of possessing certain properties, which are prescribed as requirements in the design specification. This paper studies the evolution of property predictability during the early phases of design in a case study context. By the term property predictability, we refer to the designers' confidence in predicting product properties based on the available information. In the case study, with use of the produced design models at four different stages of concept concretisation, the designers evaluated their confidence in predicting product properties related to the requirements set for the task.

As a result, we identified three different patterns of property predictability behaviour. These patterns consist of properties of which predictability is relatively high throughout the early phases of the design process, properties of which predictability shows a high increase during the progression of the early phases of the design process, and properties of which predictability remains relatively low throughout the early phases of the design process. We believe that an awareness and understanding of such different behaviours of property predictability is important for both designers and design project leaders when determining a proper timing and criteria for selecting the design concept for further development.

1 Introduction

A product is designed with the purpose of possessing certain properties, which are prescribed as requirements in the design specification. Requirements can include statements both about functional objectives, as well as about desirable attributes. It is a common understanding that early design work and the resulting selected design concept have a significant impact on the subsequent phases of the design process and on the properties of the obtained design result. However, during the early phases of design every decision and choice of solution is based on incomplete information. The nature of early design work is to formulate the design problem based on an interpretation of a need, to generate a set of design alternatives, and identify the alternative which properties are best predicted to fulfil the requirements.

The objective of this paper is to study the evolution of property predictability during the early phases of design in a case study context, and reflect on the implications this may have on design work. By the term property predictability, we refer to the designers' confidence in predicting product properties based on the available information. The authors are not aware of prior work that has been conducted to study the evolution of property predictability in the early phases of design.

The paper is structured as follows. In the following section, an overview is given on literature regarding prior work that we identify essentially related to the topic of property predictability. The research object and the utilised research method in our study are presented in section three, followed by results in section four. In section five, we discuss the results and validity of our research and discuss some implications our findings may have on design work. Finally, in section 6 we conclude.

2 Related work

We define *property predictability* as designers' confidence in predicting product properties based on the available information. We have constructed this definition based on descriptions of Buur and Andreasen. A product is designed with the purpose of possessing certain *properties*, which are prescribed as requirements in the design specification [1]. In order to be able to develop the solution that has the most potential to fulfil the specification, the focus of design work needs to be broadened to include alternative designs. Since the purpose of design work is not however to develop all design alternatives into final products, the alternative designs need to be evaluated and the most potential alternative(s) selected. Thus, the fundamental nature of design work is to generate alternatives and evaluate these according to properties [1]. To be able to evaluate the properties of the design alternatives during design, models that describe the properties of the design object need to be developed. During the early phases of design, the properties described in the design models are however incomplete. The evaluation of design alternatives during conceptual design, relates therefore to the *prediction* of the design alternatives' properties e.g. from developed design models.

We identify the following topics essentially related to property predictability:

- Requirements during the design process
- Design models
- Decisions during the early design phases

2.1 Requirements during the design process

A requirement has been defined as a characteristic, which a designer is expected to fulfil through the eventual design [2]. Further, it has been stated that the design requirement has in fact two principal roles: it serves as agreement what is wanted in an end product, and it also provides a basis for synthesizing a solution [3]. During the stages of designing, designers have the responsibility to consider the requirements of all other life stages of the product [4].

If the desired properties of the product under development could be completely determined at the start of each development project, and all these properties could be formulated into requirements, generating solutions targeted to fulfil this complete set of requirements would be possible. Additionally, at each desired stage of the design process, the properties of the design related to the requirements could be predicted. However, e.g. Almefelt et al. [5] have found in their empirical study in the automotive industry that requirements are changed, added, and reprioritised throughout the course of the development process. They point out the importance of having a flexible approach in the design process: since requirements are often incomplete and conflicting, a too strong effort to fulfil them might lead to sub-optimisation or project stagnation. In addition, requirements co-evolve with the solutions [2],[6], and new requirements are identified during solution generation [2].

Even though requirements are changed and added throughout the development process, the general approach to the design process is that a design specification including requirements is created at the start of the design task. Römer et al. [7] found in their questionnaire study that most common problems identified by designers during the task clarification phase were imprecise, changing, and late formulated requirements. Hansen and Andreasen [8] have identified that there exists several different approaches available for a design team to establish a product design specification, most of the approaches having commonality in the output as a set of specification statements. Hansen and Andreasen conclude that a set of specification statements should preferably only be one of several elements in the design specification.

Even though a design specification is created, unfortunately many requirements are not satisfied during design [2]. Nidamarthi et al. [9] have identified that unsatisfied requirements appear to often to be those that are neglected for a considerable amount of time during design process. Almefelt et al. [5] have noticed that early consideration of requirements favours their fulfilment.

Regarding property predictability during conceptual design, we see the above findings interesting. Early consideration of requirements favours their fulfilment, but on the other hand, a too strong effort to fulfil all requirements might lead to unwanted effects. From a viewpoint of property predictability, which requirements should the design team attend to during the early phases of design?

2.2 Design models

A model reproduces properties of an object, and design models vary in terms of the properties they reproduce [1]. It has further been stated that engineering design is propagation from model to model [10], and the properties that each model has in common with the object are the modelled properties [1]. Buur and Andreasen [1] further state two characteristics that are important when describing a design model: the degree of abstraction and the number of details.

Römer et al. [7] found in their questionnaire study that during the early phases of design, sketches and CAD are more frequently used product representations than physical design models. Specific representations seemed to be often used for specific functions, for example, sketches especially for solution development and CAD especially for documentation, but also for developing solutions. Physical models were often used for testing solutions and checking requirements. Further, Römer et al. found that during the early design phases sketches and models as product representations are more frequently used for the depiction of shape and function attributes, and less often to depict attributes such as manufacturing and assembly attributes.

We identify the topic of design models closely related to the research topic of this paper. In fact, the foundation for our study on property predictability is based on the design models produced during the early phases of the case study design process. The findings of Römer et al. are also the basis for one of the hypotheses of our study.

2.3 Decisions during the early design phases

The third topic of design research we identify closely related to property predictability is decisions during the early phases of design. This is based on the fundamental nature of design work, which is to generate alternatives and evaluate these according to properties [1]. It has even been expressed that in general, most design problem solving activity can be viewed as the comparison of alternatives to criteria by members of the design team [11]. Since the knowledge of the design problem grows with the progress of the project, during the early design stages every decision and choice of solution is based on incomplete information [1],[11]. Trying to evaluate more properties than the ones intended in the model may result in a false impression of the solution to be examined [1]. Macmillan et al. [12] have stated that concept generation and selection procedures may well reveal gaps in information about important elements of the design. This may mean that not even a rough and ready decision, let alone a reliable evaluation of the proposals is possible in their present state [12]. According to Ullman et al. [11], during the solution process the decision makers are repeatedly asking three questions: What is the best alternative?, Do we know enough to make a decision yet?, and What do we need to do to feel confident about our decision?. It may be necessary to develop conceptual models separately for certain distinct purposes, e.g. an assembly concept model, a service concept model, an environmental concept model etc. [10].

We identify a challenge to exist in finding a balance between generating, developing, and selecting alternative solutions during the early phases of design. In order to find the best solution from the entire set of possible solutions, the design team should explore the entire *problem space* [13]. Due to factors such as the complexity of engineering design problems and limited time and resources in engineering design practice, this is however seldom possible to the extreme. Since multiple solutions can be represented with one abstract solution, dealing with solutions on a higher level of *abstraction* [14] would be a way of bypassing this contradiction. The problem with abstract solutions is however that concrete requirements, common in engineering design, can only vaguely be applied [7]. In order to evaluate the solutions with respect to the requirements and to choose the most promising solution(s) for further development, the design team therefore has to process the abstract solutions onto a more concrete level. This however also consumes time and resources, and thus puts pressure on selecting the most promising concept for further development as soon as possible. Though solutions should be evaluated and selected at the earliest possible moment, care should nevertheless be taken not to discard valuable solutions [15].

We see the above challenge interesting from a viewpoint of property predictability. To what level of concretisation should models of design proposals be developed in order to make a rough and ready, or better a reasonably reliable evaluation of the design proposals?

3 Research method

The research methods applied in this study consist of a case study and a questionnaire study. The object of case study is the conceptual design phase of a stand-alone energy-producing plant, which was part of a product development project at a Finnish company. The product itself is based on new, developing technology. The design specification consisted of 29 individual requirements for the design task, and were categorised in seven classes as follows: Four requirements related to feasibility, four technical requirements, three requirements related to size and appearance, four requirements for manufacturing and assembly, three requirements related to installation and use, nine requirements for service, and two requirements related to product lifecycle.

The conceptual design phase of the project was conducted by the company in cooperation with the Department of Machine Design at Helsinki University of Technology (TKK), and the University of Art and Design Helsinki (UIAH). During the phases described in this paper, the core development team consisted of one mechanical engineer from the company, three mechanical engineers from TKK, and two industrial designers from UIAH.

Resulting from concept generation, five alternative plant concepts were synthesised. These five concepts were not screened at any stage, instead all five concepts were kept open until they were at a level were their properties related to the requirements could be sufficiently predicted. As a result, four stages of concept concretisation – carried by design models at different level of concretisation – during the conceptual design phase could be identified (Figure 1). Design models at the *idea stage* of concept concretisation were sketches describing the idea behind, and the form of the concepts. The *grouping stage* models described the rough layout of each concept, and the *layout stage* models described the layouts in more detail by including individual components. Models at the *final stage* of concept concretisation were used to visualise the rough appearance of the concepts, as well as show some potential service operations.

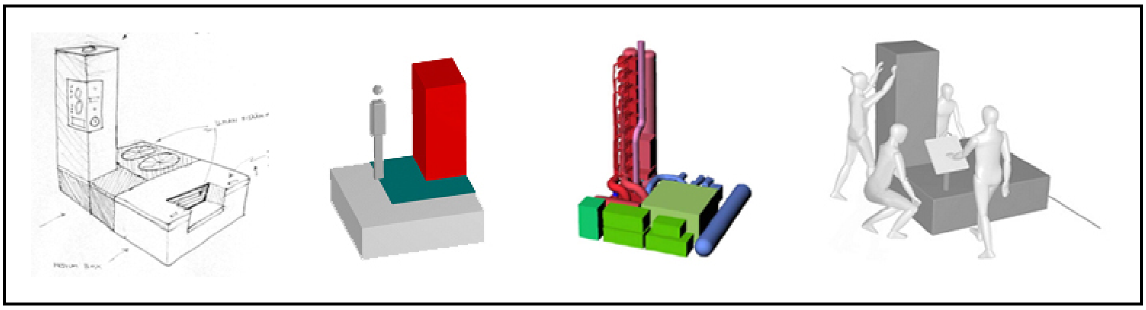

Figure 1. Four stages of concept concretisation for one of the five plant concepts, from left: *idea stage*, *grouping stage*, *layout stage*, and *final stage*

As stated by Andreasen [10], a design process can be seen as propagation from model to model. Therefore, the foundation for the questionnaire study on property predictability was based on the four identified stages of concept concretisation. The objects of the questionnaire study were three mechanical engineers and two industrial designers of the project team. With use of the produced design models, the respondents individually evaluated their confidence in predicting product properties related to each of the 29 requirements. At each stage of concept concretisation, the respondents had use of the design models of all the five concepts on that stage, as well as the models of the preceding stages. Thereafter, the authors of this paper calculated quantitative values for property predictability as an average of the respondents.

This average was further categorised as representing a low, medium, or high level of property predictability (Table 1). In addition to the overall property predictability average, average values were also calculated separately for the mechanical engineers (three respondents), and the industrial designers (two respondents).

Regarding the objects of the questionnaire study, it is further mentionable that the first author of this paper was a member of the project team (as a mechanical designer) and thus had a partial effect on the creation of the concepts. However, to avoid bias, he did not take part as a respondent in the questionnaire study related to property predictability.

Table 1. Interpretation of the qualitative responses into quantitative form, and further into three levels of property predictability

Response	Property predictability value	Property predictability level
Definitely not possible at this level	0	$0 \leq$ Low level of predictability $\leq 1/3$
Unlikely possible at this level	1/3	$1/3 <$ Medium level of predictability $\leq 2/3$
Maybe possible at this level	2/3	$2/3 <$ High level of predictability ≤ 1
Definitely possible at this level	1	

Key: Response column indicates the four alternative response options given to the five respondents in evaluating their confidence in predicting product properties related to each of the 29 requirements at each stage of concept concretisation. The presented task was: "Evaluate the possibility to take each individual requirement into consideration in evaluating the concepts at this stage"

Based on our survey of related literature, the following four hypotheses were formed for the results of our study on the evolution of property predictability during conceptual design:

1. The knowledge about the design problem and solution space grows as the design process progresses [11]. Thus, our main hypothesis for this study is that the level of property predictability will increase along with the progression of the design process as well.

2. As stated in e.g. [1],[11] during the early design stages every decision and choice of solution is based on incomplete information. Thus, our second hypothesis is that for several requirements at each stage of concept concretisation, property predictability will reach only a low or medium level.

3. Römer et al. [7] found in their questionnaire study that during the early design phases sketches and models as product representations are more frequently used for the depiction of shape and function attributes, and less often to depict manufacturing and assembly attributes. Our third hypothesis is therefore that the predictability of the size and appearance properties is among the highest in the conceptual design models of the case study, and the predictability manufacturing and assembly properties significantly lower.

4. Andreasen [10] states that it may be necessary to develop conceptual models separately for certain distinct purposes, e.g. an assembly concept model, a service concept model, an environmental concept model etc. In the case study, models were not created to depict properties related to the entire set of requirements. Thus, our fourth hypothesis is that regarding property predictability, the models fail to cover the whole spectrum of the seven requirement categories.

4 Results

The research provided results for the designers' perception of the level of property predictability related to the 29 individual requirements at four different stages of the design process. Our main hypothesis for this research was that the level of property predictability would increase along with the progression of the design process. In general, the results appeared to support this hypothesis (Figure 2). The values in the figure represent the amount of requirements at each stage falling into each level of property predictability, where the level of property predictability is calculated as an average of the five respondents. However, there also appeared to be exceptions, where the level of property predictability related to an individual requirement was actually perceived to decrease by the respondents. This can be seen from Figure 2 as e.g. the decrease of the amount of requirements possessing a high level of property predictability between the layout and final stages of concept concretisation.

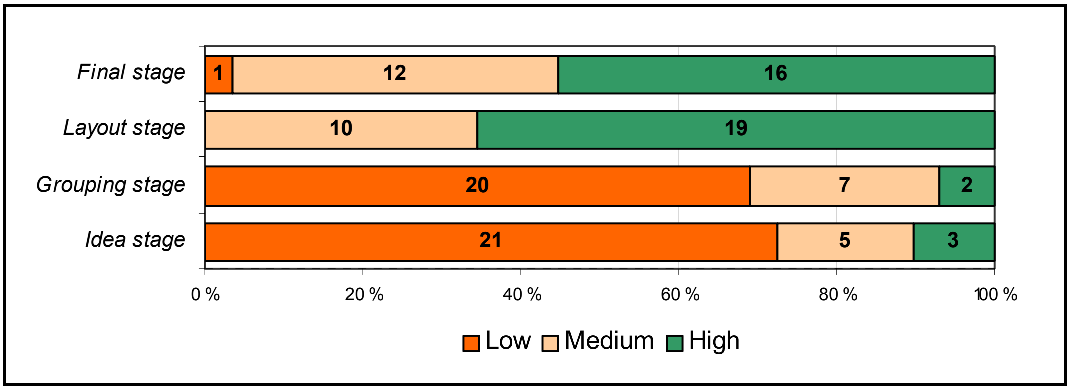

Figure 2. The level of property predictability related to the 29 individual requirements at each level of concept concretisation

The results were further grouped according to the seven requirement classes (Figure 3). The results are very similar to that of the individual requirements. Regarding our main hypothesis for the study, the results were thus unexpected. The level of property predictability did not increase along with the progression of the design process in neither all requirements nor requirement classes of the case study. An exception to our hypothesis appears to prevail at least between the layout and final stages of concept concretisation. The results clearly supported our second hypothesis for the study: for several requirements at each stage of concept concretisation, property predictability reached only a low or medium level.

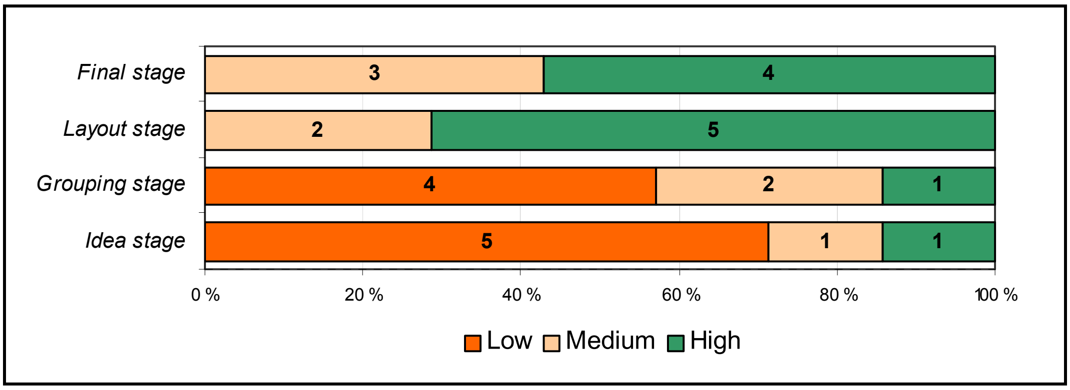

Figure 3. The level of property predictability related to the seven requirement classes at each level of concept concretisation

After analysing the results related to the evolution of property predictability in more detail, we further identified that – on a generalised level – there actually prevailed three different patterns of property predictability behaviour in the case study. Size and appearance was a requirement class where the level of property predictability was perceived relatively high throughout the early phases of the design process (Figure 4A). A similar type of behaviour was also identified to prevail for the installation and use requirement class (Figure 4B), although the perceived property predictability was not as high as for the size and appearance requirements.

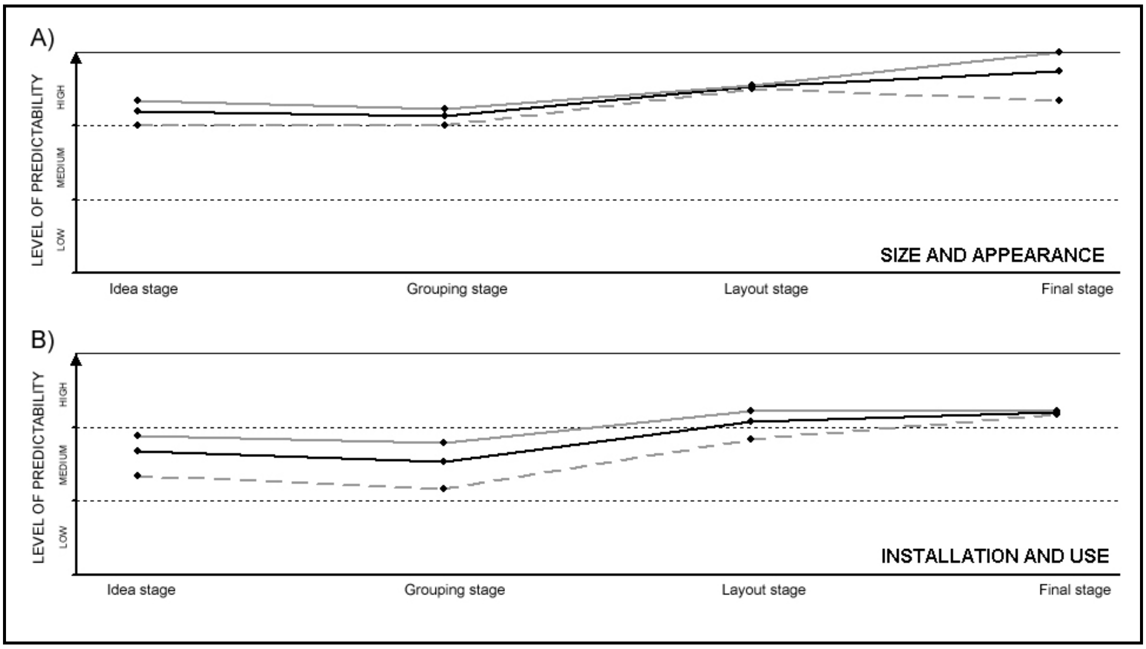

Figure 4. Evolution of property predictability in A) Size and appearance, and B) Installation and use

Key for figure interpretation: The value of property predictability for size and appearance is an average of the calculated property predictability values for the three size and appearance requirements, and the values for installation and use of the three installation and use requirements. The data points on the continuous black line represent the average of all five respondents (N=15), on the continuous grey line the average of the three mechanical designers (N=9), and on the dashed grey line the average of the two industrial designers (N=6).

Representing another pattern of property predictability behaviour, the technical, manufacturing and assembly, and service requirement classes of the case study showed a noticeably high increase in property predictability between the second and third stages of concept concretisation (Figure 5). The exceptional behaviour, where the level of property predictability was actually perceived to decrease by the respondents, can also be noticed from Figure 5.

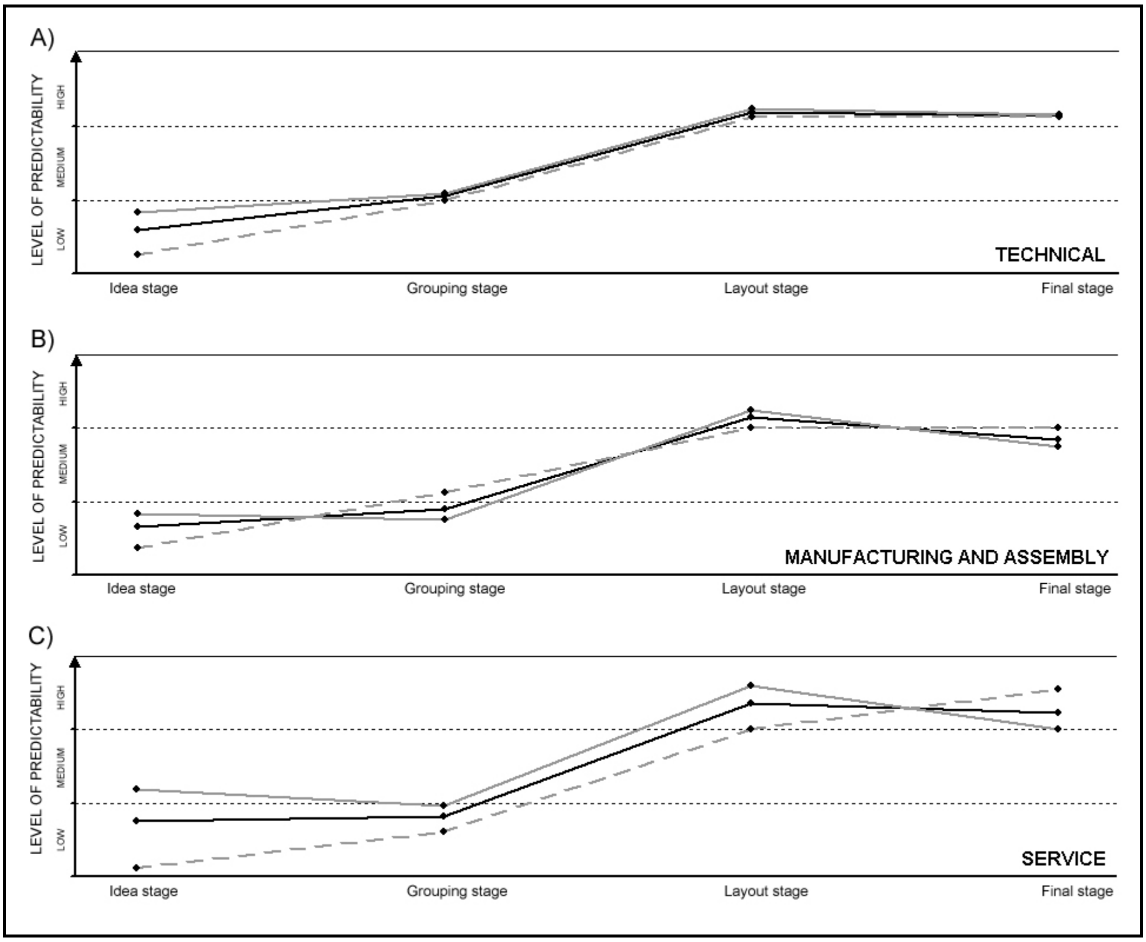

Figure 5. Evolution of property predictability in A) Technical, B) Manufacturing and assembly, and C) Service

Key for figure interpretation: The values of property predictability for technical is an average of the calculated property predictability values for the four technical requirements, the values for manufacturing and assembly of the four manufacturing and assembly requirements, and the values for service of the nine service requirements. The data points on the continuous black line represent the average of all five respondents (A,B:N=20, C:N=45), on the continuous grey line the average of the three mechanical designers (A,B:N=12, C:N=27), and on the dashed grey line the average of the two industrial designers (A,B:N=8, C:N=18).

The third identified pattern of property predictability behaviour was where the level of property predictability remained relatively low throughout the early phases of the design process. The feasibility and product lifecycle requirements incorporated this behaviour in the case study (Figure 6). This pattern of property predictability behaviour indicates that it is very difficult to evaluate some product properties during the conceptual design phase.

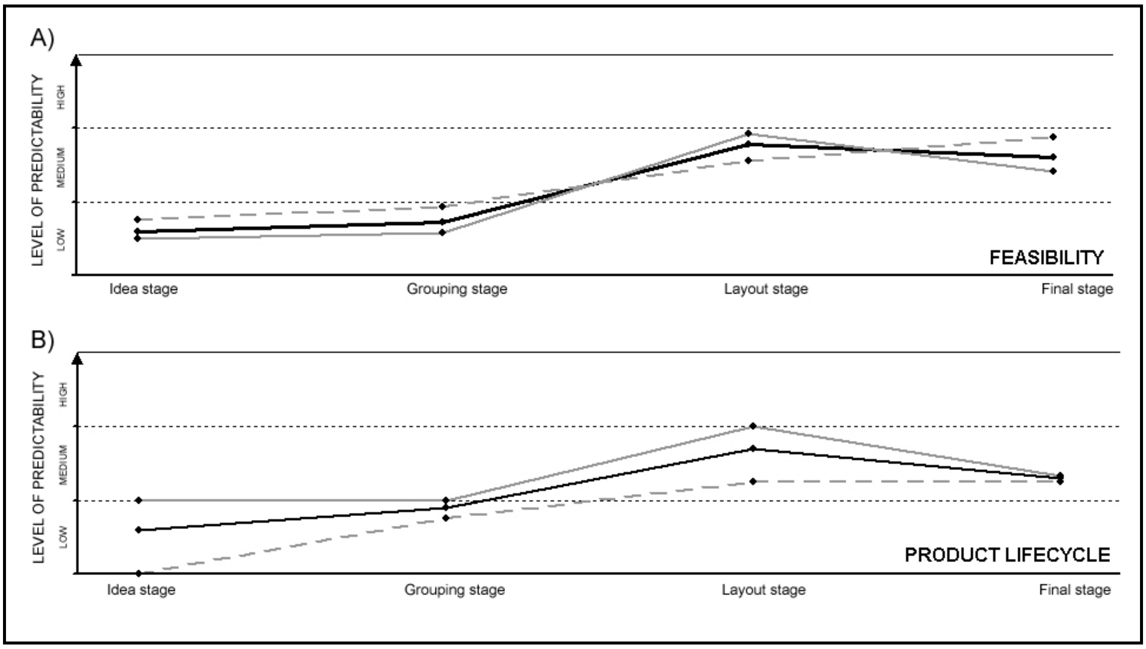

Figure 6. Evolution of property predictability in A) Feasibility, and B) Product lifecycle

Key for figure interpretation: The values of property predictability for feasibility is an average of the calculated property predictability values for the four feasibility requirements, and the values for product lifecycle of the two product lifecycle requirements. The data points on the continuous black line represent the average of all five respondents (A:N=20, B:N=10), on the continuous grey line the average of the three mechanical designers (A:N=12, B:N=6), and on the dashed grey line the average of the two industrial designers (A:N=8, B:N=4).

5 Discussion

5.1 Results of the study

Regarding our main hypothesis for the study, the results were unexpected. The level of property predictability did not increase along with the progression of the design process in neither all requirements nor requirement classes of the case study. Even though the respondents had use of the design models of all the five concepts on each stage as well as the models of the preceding stages, the latest models appeared to have had the most effect on the perception of property predictability. The layout stage concepts, with the highest level of detail, resulted therefore in the highest perception of property predictability related to many requirements. This finding implicates that the form in which the concepts are presented in, has an impact on property predictability.

The results did however clearly support our second hypothesis for the study: for several requirements at each stage of concept concretisation, property predictability reached only a low or medium level. For a concept to be selected it should preferably have not only good properties with respect to the important requirements, but also a sufficiently high level of property predictability with respect to these properties. In design projects, the proper timing of concept selection is affected also by other factors than property predictability. The justification behind proper timing should preferably be based on the overall benefits of the design process and design outcome. A conclusion reached from engineering practice is however that it is preferable to rather spend some more time on the early design stages, than on correcting problems in the later phases of development [4].

Our third hypothesis for the study was that the predictability of the size and appearance properties is among the highest in the conceptual design models of the case study, and the predictability manufacturing and assembly properties significantly lower. The findings of the case study were in line with this hypothesis. Further, there existed requirements where property predictability remained relatively low throughout the early phases of the design process. This was also as expected (fourth hypothesis), since none of the conceptual design models of the case study were created distinctly to depict properties related to these requirements. This finding also implicates the evaluation of certain product properties during the conceptual design phase to be difficult.

5.2 Validity of research

We identify and discuss here two areas that relate to the validity of our research: the object of case study and the objects of the questionnaire study.

The object of case study in this research was based on new, developing technology. The non-existence of prior versions of the product, and the issues related to applying new technology can be believed to have an effect on the predictability of product properties during the design process. However, also redesign of a product or a machine includes new design of sub-systems. In redesign, the differences in the level of property predictability in different sub-systems may be more uneven. Thus, we believe property predictability to be an interesting phenomenon also in redesign.

The second topic of discussion on the validity of our research relates to the objects of the questionnaire study. The members of the development team had little prior experience about the key technology and the product. This can also be believed to have an effect on the designers' confidence in predicting product properties during the design process. The impact and magnitude of this factor, as well as of factors such as 'design instinct' [16] of experienced designers are however out of the focus of this paper.

5.3 Implications on design work

We consider our identification of the three different patterns of property predictability behaviour an interesting finding of the case study. We believe that an awareness and understanding of such different behaviours of property predictability is important. In our survey of related work (section 2 of the paper), we raised the following questions:

- From a viewpoint of property predictability, which requirements should the design team attend to during the early phases of design?
- To what level of concretisation should models of design proposals be developed in order to make a rough and ready, or better a reasonably reliable evaluation of the design proposals?

To summarise our findings from the case study, Figure 7 represents the identified three different property predictability patterns. These can be described as:

1. Properties of which predictability is relatively high throughout the early phases of the design process
2. Properties of which predictability shows a high increase during the progression of the early phases of the design process
3. Properties of which predictability remains relatively low throughout the early phases of the design process

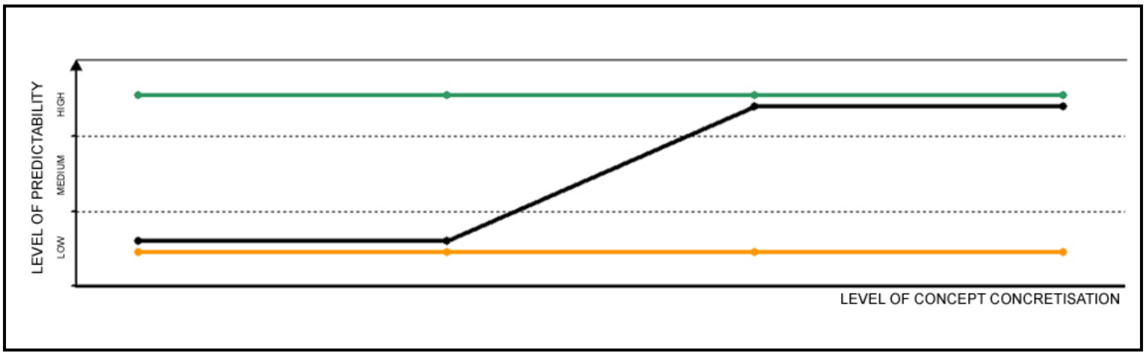

Figure 7. Identified three different patterns of property predictability behaviour during the conceptual design case study

From a viewpoint of property predictability, to which requirements should the design team then attend to during the early phases of design. We believe that the design team may gain benefits if they carefully consider the expected property predictability behaviour for important properties. In this way, the design team may avoid unpleasant surprises later in the product development project. If some important properties are expected to have the third type of property predictability behaviour, could this possibly be changed to the second type i.e. can property predictability be increased? Unless not, attending to the third type of requirements during the early phases of design does not provide much benefit to the design team. Taking these types of requirements into consideration in concept evaluation and selection would in fact not provide any well-grounded differentiation between the alternatives. A too strong effort to fulfil these requirements during the early design phases could even lead to some degree of project stagnation.

To what level of concretisation should models of design proposals then be developed in order to make a rough and ready, or better a reasonably reliable evaluation of the design proposals? Based on the identified property predictability patterns, in the case study described in this paper this 'sufficient' level is seen to have been at the third stage of concept concretisation. Having selected the concept before this stage would have been possible, but would have in fact more or less been based on only the first type of properties, properties of which predictability is relatively high throughout the early phases of the design process. This would have meant that only two of the seven requirement classes could have been considered. Having tried to evaluate more properties than the ones intended in the early models could have resulted in a false impression of the alternatives.

6 Conclusions

We have studied the evolution of property predictability during conceptual design in a case study context and have identified three different patterns of property predictability behaviour. We believe that an awareness and understanding of such different behaviours of property predictability is important for both designers and design project leaders when determining a proper timing and criteria for selecting the design concept for further development. We propose that for a concept to be selected it should preferably have not only good properties with respect to the important requirements, but also a sufficiently high level of property predictability with respect to these properties. Since property predictability remains relatively low related to many requirements throughout the early phases of the design process, it is our first key conclusion that designers and design project leaders have to carefully and consciously determine which product properties are of conceptual importance. Secondly, in order to make a well-grounded concept selection, a set of design models that carry the conceptual important properties need to be synthesised.

We do not claim the three identified patterns of property predictability to be universal. In different design projects, the evolution of property predictability might not include one or several of these three behaviours, or might include also other types of behaviour patterns of property predictability. A question for further research would thus be if other types property predictability behaviours exist. Regarding the validity of our research, we highlight two areas: the object of case study and the objects of the questionnaire study. Our case study was based on a product with new, developing technology. Having studied an otherwise similar redesign project, the identified behaviours of property predictability might have been different. Design experience can also be seen as having an impact on property predictability. These issues would be interesting topics for further research.

7 Acknowledgements

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