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TOWARDS A CO-EVOLUTION MODEL OF THE NPD-MANUFACTURING INTERFACE

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ABSTRACT
The co-evolution of the design problem and design solution has been described in Design Methodology by several authors [1, 2] and it has been recognized as a valuable contribution to our view of the front end of a design process. However, this interesting insight into the early phases of a design process has always been described in the context of a single designer performing a design task – not a very realistic situation in today's design practice. In this paper we will endeavour to go beyond this focus on the individual, by first considering what this co-evolution means in design teams, where 'shared understanding' seems to be a key factor in the social process. Then we will take yet another step, and consider co-evolution in the context of the cross-functional interface between the departments of New Product Development (design & engineering) and Manufacturing in a company. An extensive empirical study into the practices in two leading companies (in audiovisual equipment and professional lighting equipment) will inform a better understanding of the issues around co-evolution in this setting. A first description will be made, based on seeing this cross-functional process as the synchronisation of the mental models on both sides of the interface. Conclusions will be drawn for engineering design practice and education, and an agenda for further research will be presented.

Keywords: co-evolution, social process, New Product Development, Manufacturing

1 INTRODUCTION
In the conventional problem solving view of the design process, design is modelled as a reasoning process that runs from a problem to a solution (often through the mediation in terms of a functional description). The basic starting point of many descriptions has thus always been that 'in the beginning, there was the problem'. This view has been coming under fire in the last few years. (For an extensive description of the issues around the notion of design problem, see [3].) In a common view, it is now said that although design problems may be logically prior to design solutions, that one of the key features of design work actually is that in the early stages of a design project both the problem and the solution are fluid, and they change in relationship to one another. This has been described within Design Methodology as the co-evolution of problem and solution [1, 2]. According to this perspective the design process is not a matter of finding solutions for earlier defined design problems. Dorst and Cross found in their empirical work (through protocol studies of individual designers) that designers actually are aiming at the identification of matching problem-solution pairs. In the process of creating such pairs one cannot speak of creative leaps from problem towards solution, but rather of a "period of exploration in which problem and solution spaces are evolving and are unstable until (temporarily) fixed by an emergent bridge" between the problem space and the solution space. As such, this co-evolution perspective refers to the cognitive processes of one single designer in his search towards acceptable problem-solution pairs.

However, in this day and age, designers seldom work alone. Therefore an important and growing stream of research has been describing and understanding design as a social process [4, 5, 6, 7, 8]. Within this perspective, the design process is regarded as a collaborative process that aims to integrate the knowledge and skills of many actors with different functional and disciplinary backgrounds. To arrive at a balanced design that takes into account the considerations belonging to each discipline, the actors need to interact within a social process. And this social process stretches beyond the confines of the design and engineering departments within a firm: to attain the volume production of the new product the actors at the side of manufacturing also need to interact with each other and with the design and engineering departments [9, 10]. This social process between design, engineering and manufacturing is crucial during the transition from explorative product development (NPD) to exploitative manufacturing. This paper seeks to inform our understanding of design processes in practice through exploring the co-evolution of problem and solution across the interface between New Product Development and Manufacturing.

This paper is structured as follows. First we will describe how the actors on both sides of the interface, NPD and Manufacturing, are each involved in their own co-evolution processes, in the identification of promising matches between their specific problems and solutions. Then we will investigate how the professionals on both sides of the interface make sure that these two matching processes are linked together. In other words, we will investigate how the actors interact with each other in order to identify satisfying problem-solution pairs and how they transfer these from NPD to Manufacturing. In this paper we will use an extensive set of empirical data gathered in two leading professional firms to investigate how actors cope with these separate co-evolutions processes, and with the matching between them. Conclusions will be drawn for engineering design practice and education, and an agenda for further research will be presented.

2 DESIGN AS CO-EVOLUTION: FROM ONE TO MULTIPLE ACTORS

This section discusses the theoretical perspectives that form the foundations of this paper. It first introduces the notion of design as co-evolution of design problem and design solution. This view of designing has originated from the study of individual designers – not a very realistic design situation in this day and age. So the discussion of the principle of co-evolution is followed by a consideration of team designing, where co-evolutionary design is seen as a social process of cooperating design engineers.

2.1 Single designers perspective: Design as co-evolution

Designers create products that fulfil defined market needs. The product then is to be seen as the solution related to the need situation of the user. The need situation at the beginning of the design process is often described in terms of functions and requirements and in literature referred to as the design problem. However, research shows that creative design is not a matter of first fixing the problem and then searching for a satisfactory solution concept [11]. Creative design seems more to be a process of developing and refining together both the formulation of a problem and ideas for a solution with constant iteration of analysis, synthesis and evaluation processes between the two notional design 'spaces' - problem space and solution space. In creative design, the designer is seeking to generate a matching problem-solution pair, through a 'co-evolution' of the problem and the solution. Extensive protocol studies by Dorst & Cross [2] confirm that creative design involves a period of exploration in which problem and solution spaces are both evolving in parallel, and that they are unstable until (temporarily) fixed by an emergent bridge which identifies a problem-solution pairing. This 'bridge' is called ' an idea'. Ideas in design thus involve both an interpretation of the design problem and a proposal for a possible solution. One could even say that at the end of the conceptual phase, when the design concept is selected for further embodiment design, it is not the design concept itself which is 'frozen' for the rest of the design project, but the design problem.

Apart from new ideas (problem-solution pairs) the end product will also contain existing problem-solution pairs that consist of more or less proven solutions for previously solved problems. The character and amount of new problem-solution pairs and their innovativeness will differentiate the newly designed artefact from its predecessors.

The description of design as the co-evolution of problem and solution implies that we cannot presuppose that there is something like a fixed design problem at any point early on in the creative design process nor can we describe the design process as be running from problem to solution [11]. The grave doubts this raises about the stability of the 'design problem' might be aggravated when we consider the case of multi disciplinary design teams, that are made up of actors from the various engineering disciplines. This brings us to the notion of design as a social process.

2.2 Multidisciplinary design perspective: Design as social process

Most studies see design as a cognitive activity and limit their perspective to the individual cognitive actions. But, designers are not working alone. They work with colleague designers, often with complimentary knowledge, in teams or groups on the same project. This collaborative type of work implies that they have to interact with each other on many occasions during the design process. One cannot simply divide an artefact-to-be into subsystems, solve the related sub-design problems and then fit all these solutions into one coherent whole. Although one is quite capable of defining unambiguously the physical and geometric interfaces, the inevitable influences that sub-systems have on each other cannot be neglected during the design process. The (mid-term) results of individual cognitive processes need somehow to be shared with actors from other disciplines in order to detect and discuss their reciprocal influences.

Because of the different perspectives that exist among engineering disciplines this sharing of information is not just a matter of sender and receiver. It is therefore that design increasingly is seen as a social process that requires many (social) interactions among the participants as well as discussions during these interactions [4, 5, 6, 7, 8].

In order to have means for investigating the differences among the various actors Bucciarelli [4] introduces the notion of 'object worlds' as the most important influential element of the mental world belonging to the different actors. He defines such a world as follows: "a world of technical specialization, with its own dialect, system of symbols, metaphors and models, instruments and craft sensitivities" [4, p 163]. He applied this notion to designing actors from different engineering disciplines, to make clear that the different world views result in the fact that they don't share a common set of possibilities and constraints [4], and that they make use of internally consistent but different languages; they speak for instance 'structures', 'aesthetics' and 'electronics' [5]. The different problem-solution spaces belonging to the different object worlds are to some extent mutually depending on each other, meaning that choices made in electronic design might have repercussions on the possible problem-solution space of mechanical design.

For actors within design teams to have fruitful interactions among each other they need to arrive at a form of 'shared understanding' that helps them to act within the same overall frame [12, 13]. According to Kleinsmann [13] shared understanding refers to "similarity of the (individual) perceptions of actors about how the design content is conceptualized". And according to Clark & Brennan [14], shared understanding denotes a situation of "mutual knowledge, mutual beliefs and mutual assumptions".

The likelihood for shared understanding to occur among engineers with different disciplinary backgrounds is increased by the fact that they are all acting concurrently within the same design process. This is not the case for the situation we are focussing on in this paper. In a real life design situation in a design-and-manufacturing company, the actors that have to work together within the context of a development project are spread over the NPD and Manufacturing departments [9]. Both are engaged in totally different processes and their respective object worlds are far more different than between the various engineering disciplines. It therefore becomes questionable whether a similar form of shared understanding is needed to make the transition from NPD to volume production at the premises of Manufacturing.

3 DESIGNING ACROSS FUNCTIONAL DEPARTMENTS

This paper focuses on the NPD-Manufacturing interface. We will first briefly analyse this interface as one that bridges a gap between fundamentally different functions within a company: exploration and exploitation. Then we will zoom in by describing the differences between NPD and Manufacturing in terms of the fundamental differences in the mental models between the people on both sides of the interface.

3.1 The NPD-Manufacturing interface: bridging between exploration & exploitation

By developing new products and services and introducing these to the market, companies are able to renew themselves strategically and to sustain and strengthen their competitive advantage. The process of renewing their current business offerings by searching, experimenting, risk taking, and developing new and innovative products and services could be considered to form the ‘explorative’ side of the company. Creating quality & reliability through refinement, efficiency of production and focused attention through incremental innovation of existing business output forms the ‘exploitative’ side [15]. In most companies the NPD processes are undertaken separately from the Manufacturing processes (in different departments). This separation is not surprising since exploration capabilities like the development of new abilities by long-term research & ‘out of the box’ thinking and/or innovative & flexible behaviour are, more or less, the opposite of exploitation capabilities like the efficient and effective operation of present abilities by adaptive and routine behaviour.

The interface between NPD and Manufacturing departments within a company can therefore be seen as an interface between explorative and exploitative activities. The transition from the design phase to the production phase that bridges these two business processes forms the subject of this study. We are particularly interested in the processes that take place before the new design is finally handed over from the NPD department towards Manufacturing. We have observed (see Section 4) that there are many social interactions among the respective actors during this pre-production period. These interactions span the gap between exploration and in exploitation. The nature and aim of these interactions is expected to be different from the social processes as found among the designing participants that are solely operating within explorative NPD.

3.2 The NPD-Manufacturing interface: Incongruent mental models

The differences between the explorative NPD & exploitative Manufacturing processes must have considerable influence on the belief and knowledge structures as well as on the underlying assumptions behind the mental models of the respective actors. Yet the conventional view of shared understanding is based on similarities of these mental elements, rather then differences. To shed some light on the differences the actors on both sides of the interface might display and the way this influences their ability to reach shared understanding, we will make use of the notion of mental models.

Mental models are built up of “deeply ingrained assumptions, generalizations, or even pictures or images that influence how we understand the world and how we take action” [16]. Mental models become ingrained with a very deep understanding of a specialized line of work by many years of education, training, experience and activities [e.g. 16, 17, 18, 19, 20]. Because mental models are representations of the life in certain environments, they are believed to consist of both knowledge frameworks and activity structures [17] and therefore serve as knowledge and activity repositories that enable the “owners” to act and react effectively on what is happening in their environment. Because mental models are deep-rooted structures they contain besides the explicit & codified knowledge, routines and understanding also implicit & tacit knowledge, routines and understanding (Figure 1). This tacitness and implicitness refers to the difficulty to articulate and use the deep understanding and ingrained routines to support a certain viewpoint in a conversation with others.

If mental models between actors show considerable dissimilarities, and this is very likely in the case of NPD and Manufacturing, then reaching a form of shared understanding among these actors as defined above becomes questionable. Let’s have a closer look at the differences between explorative NPD and exploitative Manufacturing.

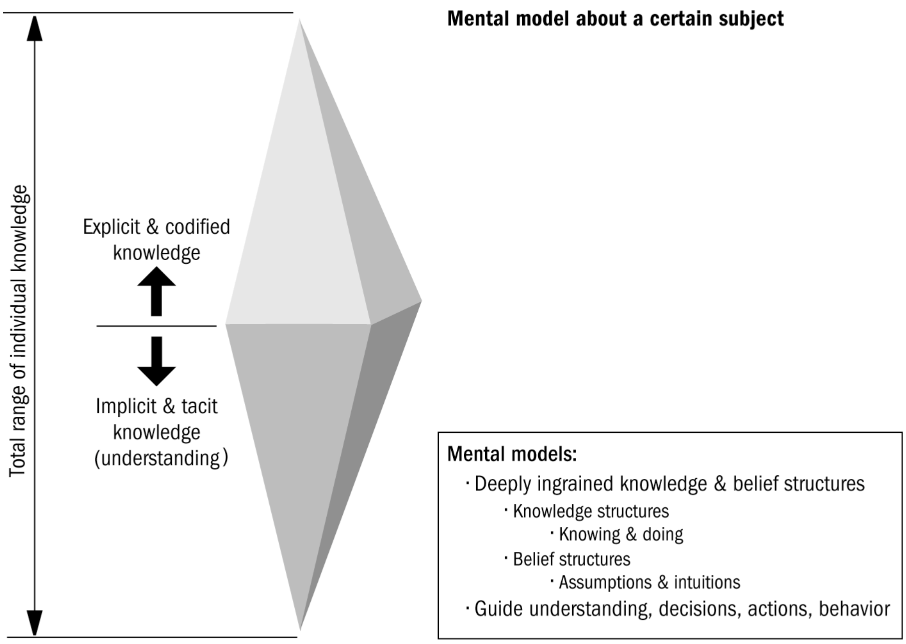

Figure 1. Schematic representation of a mental model

Designing is characterized by the absence of pre-defined procedures and its divergent, open-ended and ambiguous nature. Options are often kept open as long as possible. The mental models belonging to designers contain a large variety of knowledge structures related to materials, ergonomic issues, strength and performance issues as well as to the knowledge build up in former design projects. The routine/activity part of the Design mental model is related to the design process and design activities, in terms of sketching, visualizing, integrating, problem solving, etc. and is characterized by the acceptance of frequent and necessary iterations. During the development activities the designers build a mental model that forms an abstract representation of the product and process and contains knowledge about design decisions, design alternatives, design considerations, etc. [21]. As such, the design process is closely linked to the conceptual form of learning within organizations [17, 22].
On the other side, Manufacturing is an exploitative process that aims at quality & reliability through refinement & efficient production [15]. The production & assembly process is characterized by the convergent and close-ended activities that aim at reaching higher reliability and efficiency by increasing the amount of standard procedures and leave out all possible options by 'freezing' any situation as soon as possible. The mental models related to production and assembly will contain knowledge about a large variety of production and assembly machines & possibilities as well as a large variety of related routine activities. Once the level of volume production is reached, there is only incremental increase in knowledge related to the operational learning [17, 22].

Based on these dissimilarities it is not surprising that these two processes make use of fundamentally opposing reasoning strategies [23, 24] and that each have their own intrinsically harmonious logics and ways of reasoning [25, 26]. It can be assumed that the totally different worlds and cultures between explorative design actors and exploitative manufacturing actors in terms of activities, routines, goals, time frames, assumptions and orientation, result in dissimilar or even incongruent knowledge & activity structures that form the base of their respective mental models.
This raises questions about how actors belonging to such different worlds are able to communicate and transfer knowledge preceding the start of the production. We will explore the nature of the interactions between NPD and Manufacturing in an extensive empirical study. How do designers and manufacturing people in some of the leading companies in the world negotiate these differences? How do they allow a co-evolution of problems and solutions to take place within this context?

4 RESEARCH APPROACH

In this section we will discuss the layout of our empirical study. First we will motivate the choice for grounded theory and discuss some general issues of that methodology. This is followed by a description of the research process as applied in this study.

4.1 Choice for Grounded Theory

It was made clear that the transition from NPD to Manufacturing of a new product could be seen as going from exploration to exploitation. However, the dominance within the NPD-Manufacturing interface literature regards this interface as embedded within the product innovation process and is therefore dominated by an explorative perspective. Very little is known about the interfaces between explorative and exploitative processes, and there seems to be little understanding on how transitions from one to the other are made [24, 27]. Most research concentrates on the (strategic) balance between the two or focuses on one or the other [28]. However, in real life, companies do make transitions from exploration to exploitation by developing new products and implementing them in production environments.

To summarize it can be said that there is no theoretical framework available that:

- Describes the transition from exploration to exploitation in detail
- Describes the transition of new products from explorative NPD to exploitative Manufacturing
- Describes the social processes among the actors from NPD and Manufacturing

Since there are no theories available that describe the NPD-Manufacturing interface from the perspective chosen in this study, the interface needs to be explored in real life situations. This singles out an empirical approach for this research, a study needs to be done to identify elements and relationships among them as a basis for building a conceptual theoretical construct of the interactions. Within the empirical sciences, the inductive approach is directed from empirical data to theoretical conceptualization [29, 30] and the rhetoric tends to follow the sequence 'method, data, findings, theory' [31]. From the options within the empirical sciences, like action research, ethnography and case studies, a choice was made for grounded theory as the most appropriate method at this juncture in the project.

Grounded theory was introduced by Glaser & Strauss in 1967 [32] and formed reaction to the prevailing hypothetico-deductive research at that time and has been refined from then on [33, 34]. The research approach of grounded theory originated in the domain of sociology, but over the past decades it was applied in many other fields including the field of management and organization studies [30]. Locke [30, p. 41] writes: "Grounded theories are very much oriented towards micro level processes reflected in action and interaction. The researcher focuses on the study of patterns of behaviour and meaning which account for variation in interaction around a substantive problem in order to arrive at conceptually based explanations for the processes operating within the substantive problem area". The NPD-Manufacturing interface forms the substantive problem area that will be explored at the micro level of interactions between the actors. To arrive at a socio-interactive perspective, i.e. a description of the social process, conceptually based explanations are needed as possible accounts of the behaviour patterns that are observed in the empirical data. A grounded theory approach will also allow us to uncover and describe relevant social processes that are necessary for making the transition from explorative NPD to exploitative Manufacturing.

4.2 THE RESEARCH PROCESS

The research process of Grounded Theory is in fact one integrated process "whereby the analyst jointly collects, codes, and analyses his data" [32, p. 45]. During this so-called theoretical sampling the researcher oscillates between the two main activities: the collection of empirical data and the interpretation of that data including deciding for adjustments in the next step of data collection. One of the ideas behind grounded theory is to analyze parts of data immediately after it has been collected and then adjust the plan or viewpoint for another data collecting activity. Even during interviews the remarks of the interviewees could lead to micro adjustments within the interview protocol. "The rationale of theoretical sampling […] is to direct all data gathering efforts towards gathering information that will best support the development of the theoretical framework" [30, p. 55]. This dual track research path in which data collection and data analysis frequently overlap is 'a striking feature of research to build theory' [35, p. 538]. The goal of theoretical sampling is to collect data to the point of theoretical saturation of the emerging new theoretical concepts.

The research process within this study had three stages: scanning, focusing and integrating. The goal of the scanning stage was to develop a feeling for the relevant problematic situations regarding the interface. Therefore, a total of 65 people in three companies were interviewed, primarily in group settings. The grounded approach strives to uncover the social behaviour of actors that is aimed at resolving their main concern. Therefore we explored what the recurring critical interactions or incidents were, according to the people that participating in the processes. The interview protocol, which was based on the nominal group technique, resulted in 26 regularly occurring obstructive situations concerning the NPD-Manufacturing interface. A first induction stage with these 26 situations resulted in six preliminary theoretical categories. These first six concepts were helpful in the second, focusing, stage of the research.

During the second stage a total of 14 in-depth interviews were held in two companies (seven per company) concerning two recent product innovation projects per company (a total of 4 projects). Both companies are of average size (1000-2400 employees) and global players in their markets, respectively high-end consumer electronics and high-end lighting systems for events (pop festivals) and night clubs. The interviewees, working either in design or manufacturing, were all questioned individually in semi-structured interviews lasting 1.5 hours. During the interviews, the main topic was their collaboration with the other party, with the product innovation project being used as a 'vehicle'. The transcripts of the interviews (265 pages) were subsequently analysed and interpreted with an open mind whereby previous categories (from literature and the first research phase) were considered to be possibly relevant. A first exhaustive inductive examination resulted in 1310 text incidents related to the researched interface between development and production, and classified a total of 37 concept categories (including the previous categories). A further analysis resulted in two related central categories, one on learning and learning styles and the other on changes and interventions. Many of the other categories appeared to have relationships with these two.

The third and integrating stage of the research aimed to bring together the two central categories and interrelated properties into one core category. Given the abundance of empirical data assembled in the second stage, it was decided to use these for the third stage as well. In order to increase the theoretical sensitivity, use was made here of a number of existing theoretical concepts from the literature about learning and about change management. These existing concepts worked as a source of inspiration for the conceptualisation process in this last inductive stage. This stage is the most important one for arriving at a conceptual theoretical framework. This process encompassed numerous iterations between conceptual propositions and empirical data to ensures its groundedness.

5 DESCRIBING THE SOCIAL PROCESS

Actors from both sides of the interface mainly act from their context related mental model. For instance, an actor from Manufacturing understands why something is not going to work very well in production, but might be unable to articulate that insight and make it explicit enough that the actor from Design, who has a different mental model, understands the same point. On the other hand, the actor from Design has an implicit and thorough understanding of the new product. He knows all about the considerations and rejected alternatives that underpin the design at a certain moment. Like the implicit knowledge within Manufacturing, it is impossible to make all that Design knowledge explicit and ready to convey to other actors until they have the same deep understanding. One cannot transfer understanding, because apprehension & comprehension are individual processes that are guided by the individual mental model [36, 37]. The only thing that actors can do is to look for those knowledge components that could link the two dissimilar forms of understanding or mental models. This process of interaction that aims to connect the incongruous mental models on both sides of the interface is called **synchronization** – it is an important social process among the actors from Design and Manufacturing [9]. This is a two-sided process whereby both parties attempt to introduce the other to the understanding that resides in their own mental model. During interaction they aim to explicate the implicit part to make it available for the other. Their implicit knowledge, understanding and routines need to become explicit in order to scaffold their explicit perspective and opinion.

Information sharing occurs when participants are able to link information to their mental models through, what Postrel [38] calls, docking points. Lynn et al. [37] argue that for information to become internalized and understood it should be congruent with the mental model of the receiving individual. Thus, there must be a fit between new information and the existing mental model. If the mental models between Design and Manufacturing are incongruent then how is such a fit possible? It is

suggested here that a rudimentary mental model of the other process could provide the congruency sought for [9]. The designer uses such a rudimentary mental model of e.g. the assembly process while executing a design for assembly (DFA) strategy.
If the designers have incomplete rudimentary mental models of the assembly process or are not synchronizing enough then this will lead to engineering change orders. The following quote taken from an interview with a design engineer illustrates such a situation.

> *"…we still have a few things that our mechanical designers are working on. Another solution of … we have a glass frame… they are developing another way to do it, because it is to tricky to do it in the present way, to assemble it in the factory. Now they are assembling it in the ugly way, that will say, it is difficult for them, it takes time. It is OK for the costumer, the costumer cannot see anything, it is only it takes too much time, too difficult, …[the assembly people] have to check it too much and so on …they have to be careful about quality. So they [NPD] are working for the moment on another way to do it and it is…. in a week or two we have the solution we think, and the tools are finished, so we can get the parts for it…" (NPD.5.599)*

During the interview the transition of a newly developed product (a television set) from NPD to Manufacturing was discussed. To arrive at volume production, the people at the production and assembly line need to be able to arrive at a certain level of routine. Having a background by training or experience about the other side of the interface seem to result in such a rudimentary mental model that is of help during the social interactions as the manager from one of the production lines in Audiocom mentions.

> *"… I have a background from product development, and I know a lot about the things, and how they think and how they develop a product, the software, the hardware, the mechanics and so on. That has of course been useful when I changed to production…" (Mnfct.4.42)*

Because his former experiences he has a rudimentary mental model about the design process. But then it is a matter of keeping that knowledge up to date because of the fast pace of the developments regarding new technologies and ways of working within each of the processes. But even so, fruits of these new technological developments are not always suitable for implementation within Manufacturing. The following quote by an actor from Manufacturing reports on such a case, an interaction during development - before the actual production start.

> *"…we had a very, very long discussion with the people who are developing the test equipment, whether we should use the technology or not, because they would like us to continue using their complex technology, because they developed it, and we said no, no, we won't use it, because we have had this ramp up and we have this experience. So it was a very, very long discussion. And I worked it over a lot of times with our factory manager chief. He was, he was…. We had a platform, and I said that my group …… we said, we had this and this experience and we want to take out the complexity. And that was a long discussion …" (Mnfct.3.772)*

The actors in Manufacturing had difficulties to transfer their earlier and troublesome experiences with that same technology to the actors from NPD in order to get rid of the complexity. It took them a long time and a lot of discussion before they were able to transfer their viewpoint.

We have tried to illustrate here that the actors from NPD and Manufacturing are not aiming to arrive at shared understanding as defined within the context of design teams. There is no situation of mutual knowledge, mutual belief and mutual assumptions that provides the base for similar perceptions regarding the design content. NPD tries to get access to the implicit and tacit knowledge that resides within the mental models of Manufacturing which they need for their own development process. Once Manufacturing has delivered that knowledge or once NPD knows enough to go on, Manufacturing just returns to his day-to-day exploitative activities. Although it is a two-sided process only one of the parties is in need for information to continue his/her process. During the interactions itself, it is the main concern of the actors to identify, explicate and transfer (the meaning of) the information sought for to the other party.

6 DISCUSSION

Dorst [11] effectively suggested that there are no fixed design problems during the early stage of the design process, and this leads us to the question whether the common modelling of (engineering) design as a problem solving process serves us well. If we take the idea of co-evolution seriously, we cannot hold on to the idea that design is a problem solving process that simply runs from 'a problem' to 'a solution'. 'The problem' just is not a fixed entity, but something that is co-created in the design process. In the multifunctional collaborative design activities that we presented here the co-evolution perspective on design allows us to capture some of the real-world complications in these processes. There are actually three nested co-evolution processes that happen at the same time: one within NPD, one within Manufacturing and a boundary-spanning co-evolution process between the two. For efficient interplay among these three processes it is suggested by Smulders [38] that the respective actors need to have (at least) two mental models: one that represents their normal day-to-day work environment and one that is named the 'transitional mental model' which covers a rudimentary mental model of the other process as well as synchronizing competences.

The two co-evolution processes within NPD and Manufacturing show a lot of dissimilarities in terms of their character (assumptions & beliefs), the issues they deal with and the knowledge they apply. Yet they have to work together to form an overall co-evolution of problem and solution on a higher level. Solutions thought up by actors representing NPD might cause problems that Manufacturing then needs to solve in their co-evolution process, within the boundaries that the NPD-solution sets. One man's solution is another man's problem… The design decisions by NPD might restrict the solution area of Manufacturing, even beyond the solution possibilities of the actors within Manufacturing. Then there is no solution possible, and the only way forward then becomes to initiate late (& costly) design changes. This is what we want to avoid by studying this interface so closely, within the theoretical framework of co-evolution. We need to develop methods to make sure that these cross-interface iterations are reduced to an absolute minimum.

From the interface studied in this paper we can learn that in the NPD-Manufacturing interface, design can be seen as a process that runs from design solution as created by NPD to a 'design problem' as perceived and created by Manufacturing. A developing design proposal bounces back and forth between one problem-solution space residing within the mental models of NPD to the problem-solution spaces at the side of Manufacturing. At such instances during design activities there is not only co-evolution of the problem and the solution, but also a co-evolution of these problem-solution spaces themselves. The combined uncertainties of all these non-stable problems and solutions, problem spaces and solution spaces means that there is a real threat that people in NPD or Manufacturing will freeze some parts of the problem or solution prematurely, just to get some foothold in the design situation. This could easily lead to the development of sub-optimal solutions and it is really difficult to let go of these particular design proposals or decisions about the design problem, because this can easily be seen as undermining the very foundation of the thinking and decision making within the project. The stubborn holding on to these cherished immutable 'starting points' within the design process easily results in a clash of standpoints across the interface, while the people in the departments could and should have been more flexible. We hope that this study has shed some light on the nature of these interface problems, as a first step towards supporting the people from both sides of the interface to engage in a true and fruitful co-evolution.

The model of design a process of co-evolution has recently been developed yet another step further [3]. In this philosophical paper, the term 'design problem' itself is attacked as being very problematic from a methodological standpoint. Design problems are changeable, and they cannot be "pinned down in empirical descriptions of design activity". Design could perhaps be better described as a situated activity, as 'the resolution of paradoxes between discourses in a design situation". In the cross-functional situation described in this paper, the paradox is represented by the opposition of views that exist among the respective actors from NPD and Manufacturing that each represents a different (even 'incongruent') discourse. The clash of conflicting discourses and the subsequent resolution is then formed by what was described here as the social process of synchronizing and made possible by the fact that actors are able to be partly engaged in each other's discourse. This in turn is made possible because of the rudimentary mental models that each actor is supposed to have of the process on the other side of the NPD-Manufacturing interface.

7 CONCLUDING REMARKS

It is too early to draw hard and clear conclusions regarding design practice and design education on the basis of this preliminary study. But the insights as presented in this paper do point at some interesting challenges regarding design education. We will mention one here. Teaching students how to interact with non-designing stakeholders that have incongruent mental models might provide them with some of the competences that are needed for effective engagement in social processes across the boundaries of the design and engineering activities. Students have to learn to develop the transitional mental model, and for this they need to have rudimentary mental models about the problem spaces and solution spaces of the people in Manufacturing. It is clear that they will need to develop into bridge-builders between these disciplines. These bridge-builders (like the interviewee from the second quote in section 5) are vital because they allow a true and free co-evolution to occur across the boundaries of the NPD and Manufacturing departments. More research is needed to pinpoint the specific properties that such a bridge-builder must have to work effectively, and on the identification of specific boundary-spanning strategies that these bridge-builders could employ.

From the research that this paper has reported on it becomes clear that the large differences between explorative NPD and exploitative Manufacturing provides additional insights regarding the theoretical perspectives that forms the foundation of this paper: that of design as co-evolution of problem and solution. One lesson to learn is that to be realistic in our modelling of design, we need to enlarge the scope of design research projects from the focus on a single designer to designers in multidisciplinary and multi-functional situations. The additional stakeholders within and outside of the design department have a profound effect on the actual design processes. It is necessary to examine whether the assumptions that presently underlie design methodological theories, and that were largely based on observations of single acting designers are still valid and relevant for describing design in these multi-stakeholder, multi-functional design situations.

The empirical data from this research project that included these additional influences seems to point towards the need for an extension of our theoretical framework for looking at design. The classic problem-solving framework needs to be augmented by other views on the design activity, like the co-evolution framework and possibly the modelling of design as the ‘resolution of paradoxes between discourses in a design situation’ [3]. Some of the basic problems and limitations that we are running up against in present design methodology might be fruitfully tackled by regarding design as a social process. The closer we look at design, and the closer we try to model design, the more fascinating and complicated it becomes.

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