# Coherent Architecture Development as a Basis for Technology Development

PhD Thesis

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Poul Martin Ravn
DCAMM Special Report No. S215
December 2015

**DTU Mechanical Engineering**
Department of Mechanical Engineering

# Coherent Architecture Development as a Basis for Technology Development

by

Poul Martin Ravn

For fulfillment of the degree

Philosophiae Doctor

Department of Mechanical Engineering

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**Coherent Architecture Development as a Basis for Technology Development**

PhD Thesis

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2015

Section of Engineering Design and Product Development

Department of Mechanical Engineering

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# Abstract

The subject of this PhD thesis is architecture-centered design. It elaborates especially on two specific areas: the coherence in architectures in a technology development context and the identification of critical development areas via property-based reasoning, based on an understanding of cette coherence.

Despite the acceptance and results presented in multiple studies from the application of architectures, the research on architecture work in a technology development context is limited.
Technologies are often developed and represented in the form of product sub-systems that are made available for product developers. Technologies, which in their infancy indicate a 'jack of all trades, master of none', have a risk of being developed without a clearly defined need or identification of which products it can be used in.

A common approach for developing such a technology includes exploration of what the sub-system that carries the technology is, how the sub-system is produced, and how it can be used in new products by means of early prototypes. Developing the prototypes will help identify the needs and requirements to which the technology must prove successful. This coherence between product sub-system, production, and testing in prototypes is essential for identifying the critical areas for development.

This research contributes to the vocabulary and understanding of coherent architecture development in a technology development context, where novel technology is developed.
In order to study coherent architectures in a technology context as a basis for identification of critical development areas, this research has been focused around the following three areas:

1. Product architecture instances for prototypes testing novel technology.
2. Product architecture definition for a sub-system based on a novel technology and the appertaining production architecture needed to realize this sub-system in a given solution space.
3. Coherent architecture as a basis for identification of critical technology development areas.

The two main contributions that are found in this thesis are: The Technology Prototype Product Architecture Tool, developed as part of point number one, and the framework for identification of critical technology building blocks, developed as part of point number three. Additional contributions are found as part of point number two through research on product architectures and production architectures represented through the Conceptual Product Platform tool and the Production Architecture Framework.

The frameworks and tools developed as part of this thesis were developed as part of deep industrial involvement in the Innovation Fund Denmark DEAP project from 2012 to 2015. The results presented in this PhD thesis were gained through active participation in the project.

*Keywords: technology development · prototype · product modeling · product architecture · property reasoning*

# Resumé

Emnet for denne Ph.D.-afhandling er arkitektur-centreret design. Den eksisterende viden udbygges her specifikt på følgende to områder: sammenhæng mellem arkitekturer i en teknologiudviklings-kontekst og identifikation af teknologiområder, som det er kritisk at udvikle gennem egenskabs-baseret ræsonnement baseret på en forståelse af netop denne sammenhæng.

Forskning i arkitekturer i en teknologiudviklingskontekst er meget begrænset på trods af, at adskillige studier præsenterer resultater og accept af anvendelse af arkitekturer i produktudviklingskontekst. Teknologier bliver ofte udviklet og repræsenteret i form af delsystemer af produkter, der bliver gjort tilgængelige for produktudviklere. For teknologier, som i de tidligste stadier indikerer "god til mange ting men ikke bedst til noget bestemt", eksisterer der den risiko, at de bliver udviklet uden et klart defineret behov eller uden klar indikation af hvilke produkter, der kan drage nytte af teknologien.

En almindelig tilgang til at udvikle en sådan teknologi inkluderer en undersøgelse af, hvad det delsystem, som bærer teknologien, består i, hvordan delsystemet produceres, og hvordan det kan bruges i nye produkter gennem udvikling af tidlige prototyper. Udviklingen af prototyper hjælper til at identificere de behov og krav, som teknologien stilles op imod. Denne sammenhæng mellem produktets delsystem, produktion, og test af prototyper er essentiel for at kunne identificere kritiske områder for videre udvikling.

Denne forskning bidrager til begrebsudvidelse inden for fokusområdet og forståelse af sammenhængende arkitekturudvikling i en teknologiudviklingskontekst, hvor en ny teknologi er under udvikling. For at undersøge sammenhængende arkitekturer i en teknologiudviklingskontekst som basis for identifikation af kritiske udviklingsområder, har denne forskning været fokuseret på de følgende tre områder:

1. Instanser af produktarkitekturer for prototyper hvori der testes en ny teknologi.
2. Definition af produktarkitektur for et del-system baseret på en ny teknologi samt den tilhørende produktionsarkitektur, der kræves for at realisere dette delsystem i et givent løsningsområde.
3. Sammenhængende arkitekturer som basis for identifikation af kritiske udviklingsområder for en teknologi.

To hovedbidrag der findes i denne afhandling er: værktøjet "Teknologi-Prototype-Produkt-Arkitektur", udviklet som del af første punkt, og rammeværktøjet til at identificere kritiske teknologi-byggeblokke, udviklet som del af tredje punkt. Yderligere bidrag findes som del af punkt nummer to gennem undersøgelse af produkt og produktionsarkitekturer præsenteret gennem værktøjet "Konceptuel Produkt Platform" og rammeværktøjet "Produktionsarkitektur".

De værktøjer og rammeværker der er udviklet som en del af denne afhandling, blev udviklet gennem omfattende industriel involvering i InnovationsFondens DEAP projekt i tidsperioden 2012-2015. Resultaterne præsenteret i denne Ph.D.-afhandling blev opnået gennem aktiv deltagelse i projektet.

*Nøgleord: teknologiudvikling · prototype · produktmodellering · produktarkitektur · egenskabs-ræsonnement*

# Preface

The research presented in this dissertation relates to the results of the research program conducted at the Section of Engineering Design and Product Development at the Technical University of Denmark (DTU). The project has been completed with strong ties to the Innovation Fund Denmark DEAP project (2011-2015). The Innovation Fund Denmark (formerly the Danish National Advanced Technology Foundation) co-funded this research together with DTU.

The research was initiated on July 1st, 2012 and concluded with the hand-in of this dissertation November 30th, 2015. The duration of the research was 36 months with 5 months granted leave in 2014.

The work presented in this dissertation is concentrated around two main topics: modeling of prototype, product, and production architectures in technology development and property reasoning in the strategic planning of the technology development process.

During the research project I have interacted with a number of persons, who in one way or another have contributed to my work and to whom I am very grateful.

First of all I would like to thank Professor Niels Henrik Mortensen for encouraging me to take on the PhD as a succession to my master thesis: one that had also focused on work with technology development and prototype development. The PhD project has been a good personal, as well as professional challenge. I would also like to thank co-supervisor Professor Lars Hvam for valuable input on different occasions.

From the section, Professor Emeritus Mogens Myrup Andreasen and Associate Professor Claus Thorp Hansen deserve a big thank you for interesting and challenging discussions throughout all three years.

In his role as company representative, Project Manager Jens Juul Yde deserves special thanks for his invaluable input and for allowing interesting discussions to take the time they take. I have learned a lot from your drive and passion. I would also like to thank the industrial and academic project partners I have interacted with during the Innovation Fund DEAP project. It has been a pleasure to exchange and discuss ideas on both a professional level and a personal level.

During the time of the PhD study I have been part of the Product Architecture Group at the section which has provided me with a vast amount of experience and knowledge. I would like to thank the highly skillful colleagues that were part of the group, both past and present. Thanks to Tómas Vignir Guðlaugsson, as my closest colleague in the Section, for collaboration and support in the DEAP project, and Troels Victor Jensen for a lot of serious and not so serious discussions.

My colleagues in office 133 also deserve a thank you. The discussion of relevant topics has been a major support to develop ideas.

I would also like to thank the international network I have built during the PhD for the interesting inputs and discussions over the years. It has been a positive experience to exchange ideas with like-minded international researchers.

To those who have contributed but have not been mentioned, consider this my thanks for your input and thoughts.

Last but not least I would like to thank my family:
Thank you to my parents for being there for discussions during both ups and downs and for "reading" when I did not want to discuss. To my sister Helene and to Michael: thank you for small-talking when I was and was not mentally present.
To Lone, my deepest thanks for supporting me all the way through these three years and for making sure that I also remembered to relax.

Poul Martin Ravn
Kgs. Lyngby
November 2015

*"The only way of discovering the limits of the possible*
*is to venture a little way past them into the impossible."*
- Arthur C. Clarke, 1962

# Publications – First Author

Paper A | Conference

Ravn, P.M., Guðlaugsson, T.V., Mortensen, N.H., **Tasks and challenges in prototype development with novel technology – an empirical study**, Conference proceedings of ICED 2015, Milan, Italy, presented July 28th, 2015.

Paper B | Journal

Ravn, P.M., Guðlaugsson, T.V., Mortensen, N.H., **A multi-layered approach to product architecture modeling – Applied to technology prototypes**, Journal of Concurrent Engineering: Research and Applications, published online July 2nd, 2015.

Paper C | Journal

Ravn, P.M., Mortensen, N.H., Hvam, L., **Identification of critical technology building blocks**, Submitted to journal.

Paper D | Conference

Ravn, P.M., Guðlaugsson, T.V., Mortensen, N.H., **Visual Modelling of Pilot Production to Support Decision Making in Production Development**, Conference proceedings of DESIGN 2014, Dubrovnik, Croatia, presented May 22nd, 2014.

The publications submitted and published as first author are considered main research outcomes. Both journal papers and conference papers have been peer-reviewed.

# Publications – Second Author

## Paper E
Journal

Guðlaugsson, T.V., Ravn, P.M., Mortensen, N.H., **Front End Conceptual Platform Modeling**, Concurrent Engineering: Research and Applications, published online August 28th, 2014.

## Paper F
Journal

Guðlaugsson, T.V., Ravn, P.M., Mortensen, N.H., **Modelling production architectures in the early phases of product development**, Concurrent Engineering: Research and Applications.

The publications submitted and published as second author are adding to the main research outcomes.

# List of Abbreviations

The following abbreviations have been used in the thesis:

| Abbreviation | Meaning |
|---|---|
| AR | Action Research |
| ARC | Area of Relevance and Contribution |
| B&O | Bang & Olufsen |
| CPP | Conceptual Product Platform |
| CS | Case Study |
| CTBB | Critical Technology Building Block |
| DEAP | Dielectric Electro Active Polymer |
| DHS | Danfoss Heating Systems |
| DNATF | Danish National Advanced Technology Foundation |
| DRM | Design Research Methodology |
| DPP | Danfoss PolyPower |
| EDPD | Engineering Design and Product Development |
| IFD | Innovation Fund Denmark |
| IPR | Intellectual Property Rights |
| PA | Production Architecture |
| PbTb | Problem-based and theory-based |
| RQ | Research Question |
| TePPAT | Technology Product Prototype Architecture Tool |
| ToD | Theory of Domains |
| TTS | Theory of Technical Systems |
| SE | Systems Engineering |
| WP | Work Package |
| WS | WaveStar |

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*"Any sufficiently advanced technology is indistinguishable from magic."*
- Arthur C. Clarke, 1973

# 1 Introduction

*This PhD thesis describes a research project in which architectures and technology have been main foci. The research puts emphasis on the tasks and challenges in technology development, architecture modeling in technology development, and selection and prioritization of technologies.*

*This first chapter introduces the background and problem area as well as the scope and structure of the thesis.*

As a first part of the introduction, the background and problem area will be explained.

## 1.1 Background and Problem Area

The main topics for this thesis are architectures and technology development. This section will provide the rationale and background for the phenomena studied in this thesis.

### *1.1.1 Developing Technology*

Technology development has for many years been a part of how new capabilities and knowledge is gained in companies. Technology development is one of the ways that companies can keep ahead of competitors (Baughn & Osborne 1989; Iansiti 1995). The application of novel technology can enable completely new products or new or better product or process capabilities. Some technologies can be straight forward to develop while others have proven challenging and taking a long time to develop. Examples can be found of technologies that, even though having been developed for two decades and having cost more than DKK 1,5 billion (~ EUR 200 million) to develop, prove not to be ready for commercial exploitation (Godske 2014).

The technology-intensive industry has through the decades been an object of investigation by a number of researchers. Some of the challenges linked to developing a novel technology are that:

- New technology will not automatically fit into existing applications (Tanner et al. 1989; Møller 2002).
- Changes are not limited to single elements, but a multitude of other design elements that together make up the system (Henderson 1990).
- The performance of the novel technology is initially lower than that of previous or competing technologies (Christensen 2009b).
- The detailed properties of the technology are uncertain (Iansiti 1995).
- There is uncertainty about the technology in the dimensions of performance, schedule, and budget (Mankins 2009a).

- The technology needs to be robust (Schulz et al. 2000).
- Tight schedules are incompatible with time needed for innovative, breakthrough solutions (Schulz et al. 2000; Iansiti 1995).
- Appropriate processes, methods, and environments are lacking (Schulz et al. 2000).

For a technology to be a winning technology, four aspects should, according to Schulz (2000) be fulfilled:

- Superiority – to ensure that the technology offers improvement in terms of cost or product differentiation.
- Robustness and Maturity – to ensure robust functionality without compromise on superiority.
- Flexibility – to ensure that the right requirements have been defined and the right noises have been imposed, so that proven applicability in the initial product program and application can enable use in various product programs.

These four aspects also set requirements for the systems in which the technology is found. As a novel technology is often introduced in a sub-system of a product, the four aspects relate to the principle of the technology in a potential product which has to be defined, i.e. an understanding of product and application coherence, the understanding of coherence in product and production to take into account flexibility in the technology, as well as robustness.

Therefore, this thesis investigates the development of coherent architectures and uses this as a base for an indication of the attention points that need to be developed further to increase performance.

### *1.1.2 Challenges in a Danish Technology Development Project*

In 1995 researchers at the Danish company Danfoss A/S started to investigate an innovative technology: the di-electric electro active polymer (DEAP) technology. The technology was regarded as having huge potential for the development of artificial muscles (Andersen 2012). A breakthrough came in the mid 2000s when the world's first production line for the technology was realized and the company Danfoss PolyPower A/S was established in 2008 to mass produce DEAP thin film (Andersen 2012).

However, being the first to define the production line led to Danfoss PolyPower taking on the task of developing the full value chain out of necessity for moving forward with the technology. If each part of the value chain was to be investigated and developed as independent projects serially, a risk of a development time of more than 20 years was likely. This was not a viable business plan.

Instead, an approach was initiated where the different parts of the value chain were developed concurrently in a joint technology development project, shaped as a public-private partnership project (Hansen 2013). Instead of 20 years of development time, it was now cut to four years. Running the projects in parallel did however increase the complexity, as well as the dependencies in the project. Performance in one project depended on deliverables from other projects.

Another major challenge with the DEAP technology was its versatility – it had the potential to be used in many industry applications, either as an actuator, a generator, or a sensor, but the main application had not yet been identified.

To tackle this, the development was structured into development of the sub-system in the form of a transducer based on the DEAP thin film, development of the production system needed for the realization of the sub-system, as well as development of prototypes to test the technology in diverse applications. In retrospect, the project was described as the following by a work package leader:

> *"Everything had to be developed from scratch, nothing had been proven. This multiplied the uncertainties."*
>
> \- work package leader reflecting on the project during a review meeting.

To reduce these uncertainties, an architecture-centered approach was adopted. Using architectures was expected to introduce some of the benefits achieved in product development, such as:

- Integration support – to identify the most critical integration barriers for the technology when integrating it into products.
- Scalability – to identify critical scaling principles when scaling the technology in both product and production dimensions.
- Variants – to identify what variants were needed to cover the diverse requirements from the possible industry applications.

Running the projects concurrently, pushing the performance boundaries, and increasing the knowledge about the technology radically, illustrated that each of the areas of development had to be taken into account as a coherent entity under development.

The example given with the DEAP technology is far from the only case in history about a novel technology being developed (Tanner et al. 1989; Utterback 1974). However, it serves as the main case for this research.

## 1.2 Scope of Thesis

The research presented with this thesis is a response to the challenges described above: investigating the coherence between different architectures as a basis for directing the technology development.

Recent contributions illustrate that the research within product architecture and platforms has an impact and is to be taken seriously (Simpson et al. 2006; Simpson et al. 2014; Jiao et al. 2007). However, architecture is a very broad area of research. Therefore the scope of this thesis is focused on the coherence between architectures linked to application, product, and production. Thus, market architecture (Hansen et al. 2012) is not within the scope of this thesis.

Recently, a focus has also been directed towards the benefits of providing a platform approach from a technological perspective. This branch has been characterized by the definition between product platforms and technology platforms (Nasiriyar 2010; Levandowski et al. 2012); however, the area has not argued for the application of architectures as a means to leverage the advances of a technology in its early stages. Therefore, the scope of the thesis is focused on this area.

## 1.3 THE CORE OF THE RESEARCH

The core of this research can be condensed into what is represented in Figure 1. The first is investigating the coherent development of three architectures for application, product and production. The second is the prioritization based on an advanced understanding of the architecture coherences.

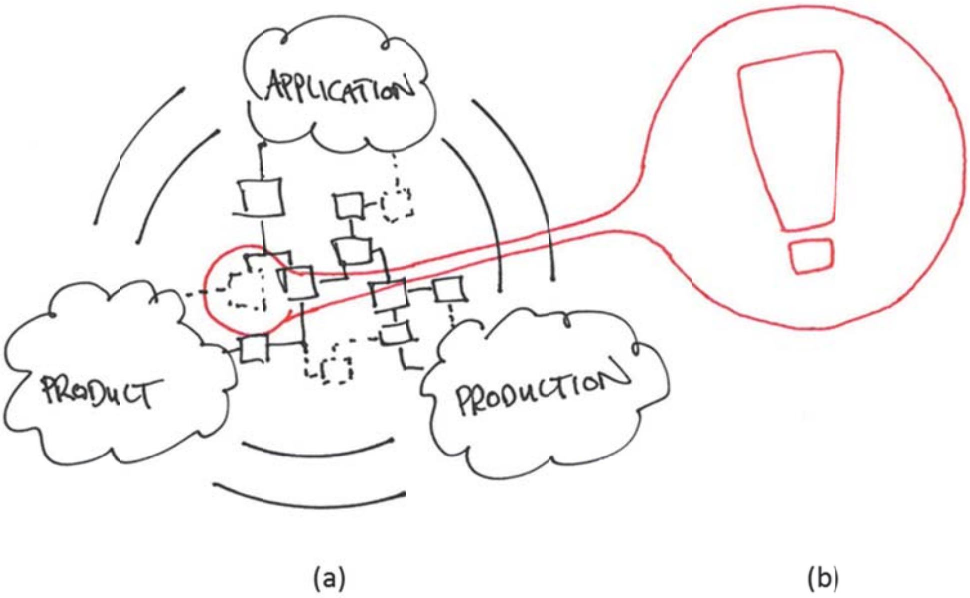


**Figure 1 - The main scope of the thesis (a) coherent architectures (b) prioritization based on coherence**

Comments on (a), coherent architectures:

- The application is here referred to as the device or product in which the sub-system encapsulating the technology is intended to be a part of.
- The product is here referred to as a sub-system encapsulating the technology.
- The production is here referred to as the production setup needed to produce the sub-system encapsulating the technology.

Comments on (b), prioritization based on coherence:

- Prioritization is here referred to as the many choices that have to be taken in a development context.

The aim of the research is:

- To investigate the use of product and production architecture approaches in a technology development setting.
- To investigate the support that such approaches can provide in a technology development setting.
- To investigate how this coherence between architectures can be utilized to direct the technology development.

## 1.4 Structure of the Thesis

The thesis is divided into 11 Chapters of which eight are presented in Figure 2:


**Figure 2 - The thesis structure**

**Chapter 1** Introduces the problem area, challenges, and the scope of the thesis.

**Chapter 2** (Research Approach) presents the research objectives, research questions, research scope, research methods, research planning, and the research validation.

**Chapter 3** (Theoretical Base) presents the theories used to obtain an understanding of four main areas: systems, technology, integration, and architectures and platforms.

**Chapter 4** (Practical Base) introduces the industrial project followed through the three-year period of the research project.

**Chapter 5** (Results) describes the results from the research based on the academic papers produced.

**Chapter 6** (Conclusion) presents the main conclusions of the research.

**Chapter 7** (Further Research) indicates possible areas for further and future research.

**Chapter 10** (Appended Articles) contains the academic contributions in the form of journal and conference papers produced during the research.

Chapters 8, 9, and 11 contain Concluding Remarks, References, and About the Author, respectively.

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*'Come, Watson, come!' he cried. 'The game is afoot.'*
- Sherlock Holmes, The Adventure of the The Abbey Grange

# 2 Research Approach

*This chapter presents the research approach for this PhD project.*

*First, the research questions are described. Then, the research scope is introduced, followed by the research method. After this, the research verification approach is described and research planning concludes the chapter.*

The PhD project has been carried out as a collaboration project between the Innovation Fund Denmark DEAP project and the Technical University of Denmark (DTU), at the Department Mechanical Engineering, in the Section of Engineering Design and Product Development (EDPD), as part of the Product Architecture Group.

## 2.1 Research Questions

For this thesis project the research questions focus on different aspects of architecture coherence and integration in technology development projects and have different approaches regarding how they have been explored. The research questions are divided into three main areas: Product architecture instances for prototypes testing novel technology, Product architecture and production architecture in early development setting, and Architecture coherence as a basis for prioritization.

**Research Area 1 –** Product architecture instances for prototypes testing novel technology

The first research area has focused on the development of prototypes in a technology development setting.

**RQ1a** - What are the tasks and challenges of developing prototypes with input of a novel technology?

Research question 1a is explorative in nature and seeks to provide an explanation to tasks and challenges in technology development in the specific setting of prototype development.
Prototypes are man-made constructs used to increase knowledge of how a particular device will work. Novel technology is referred to as new know-how.

**RQ1b** – How can the combination of a new technology and part of an existing product be understood as a prototype?

In order to understand integration of new technology, research question 1b is used to gain an understanding of a description of prototypes, based on existing and new know-how in a combinatory sense.

Research question 1c seeks to understand the specifics about product architectures in prototypes by understanding how these can be modeled in a technology development setup.

**RQ1c** - How can product architectures of prototypes be modeled in a technology development setup?

Research question 1c is used to provide a model for the representation of prototype architectures.
A model is used in the meaning graphical model, i.e. a 2D representation of the object modeled.
Architecture is understood as the purposeful arrangement of a structure in a device.

**RQ1d** – What are the effects of using a product architecture model representation for prototypes in technology development?

Research question 1d is used to explore the effects of product architecture representations in a specific context. Effects are here understood as a change in situation.

**Research Area 2:** Product architecture and production architecture in early development setting

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Research area 2 was running concurrently with research area 1 and was highly linked. Research question 2a is used to investigate how requirements from the prototypes investigated in research area 1 are related to a product architecture for the sub-system in which the technology is realized.

**RQ2a** – How can diverse requirements from multiple application areas be related to a product architecture defining a platform in early development stages?

Research question 2a concerns the product side of the sub-system containing the technology, used in the prototypes.

**RQ2b** – How can diverse requirements from multiple application areas be taken into regard in production architectures in early development stages?

Research question 2b is related to the production of the sub-system containing the technology. Here, other technologies need to be mastered in the specific setup that enables a desired quality, cost etc. of the sub-system.

**Research area 3:** Architecture coherence as a basis for prioritization

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Research area 3 was a result of the two former, seeking to understand how the coherent architecture development could be used as an advantage to prioritize the next development areas.

**RQ3a** – What structure can be identified for coherent architectures to enable a complex system understanding?

Research question 3a is used to understand the coherence between prototype, product and production which are being developed concurrently.
The term structure is here used to describe part-of relations, kind-of relations, and dimensional relations.

**RQ3b** – How can architecture coherence be used to identify and prioritize critical areas in the development?

Research question 3b is used to investigate the use of property reasoning to identify critical areas in the development.

## 2.2 Research Scope

The scope of the research is focused around the development of novel technology. Here, the specific research area is introduced, as well as the limitations.

### *2.2.1 Research Area*

To capture the identification and exploration of the focus areas of this research, as well as defining the boundaries for this research, the Areas of Research and Contributions (ARC) model was used (Blessing & Chakrabarti 2009). The model was used to emphasize and highlight the research phenomena that have been relevant for, or contributed to, this research (please see Figure 3).

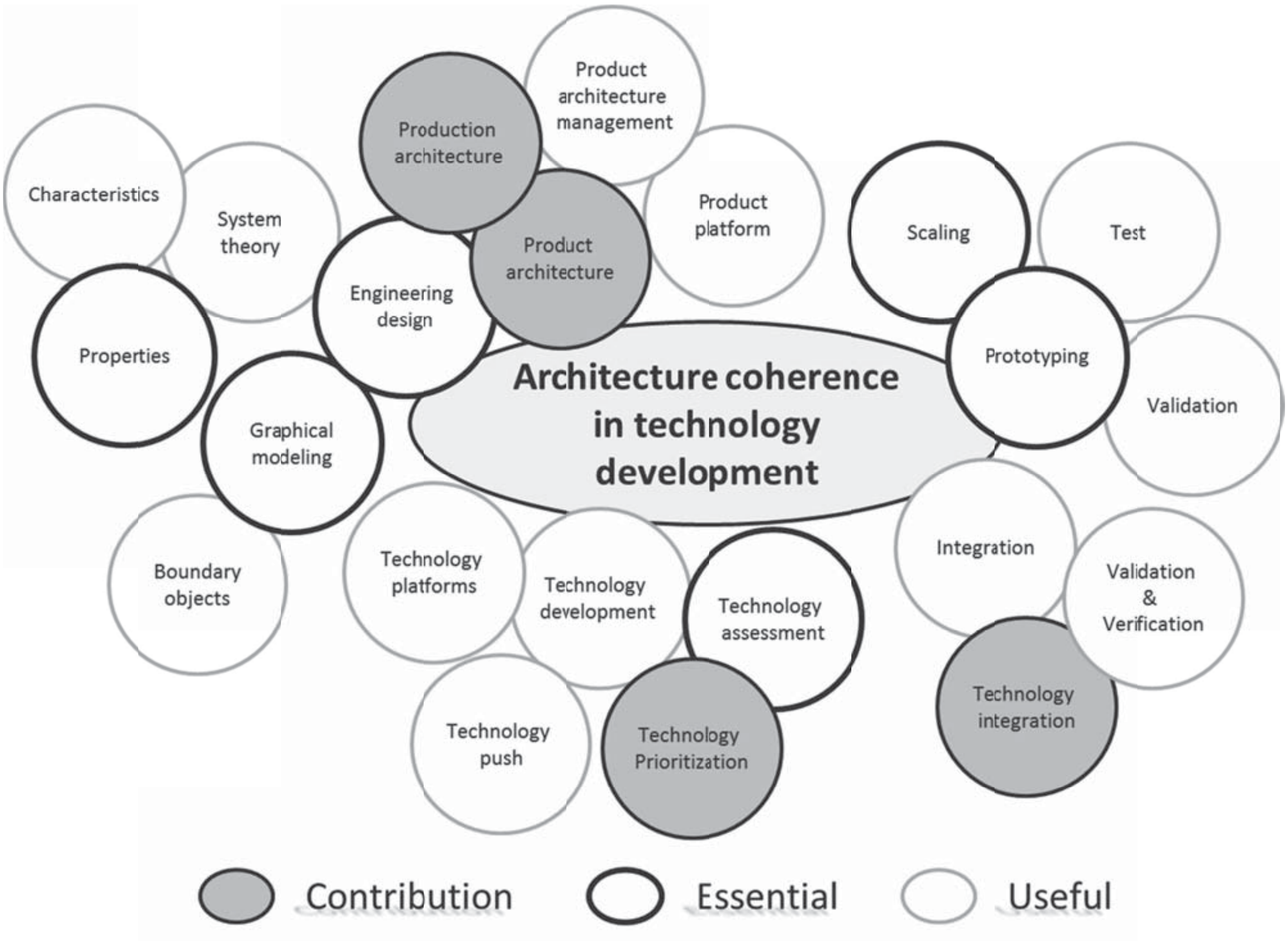


**Figure 3 - ARC model for this project with marking of useful, essential, and contribution areas**

The center of the model represents the main research subject for this research. The main area of research is stated to be within the area of architecture coherence in technology development. The adjoining areas are found in four main clusters: "Engineering Design", "Prototyping", "Integration", and "Technology development".

The top left cluster, *Engineering Design*, is represented by three main branches. One with *System theory*, *Characteristics*, and *Properties*, a second with *Graphical modeling* and *Boundary objects*, and a third with *Product architecture*, *Production architecture*, *Product architecture management*, and *Product platform*. The top right cluster, *Prototyping*, consists of *Scaling*, *Test*, and *Validation*. The lower middle, *Technology development*, includes *Technology push*, *Technology platforms*, *Technology assessment*, and *Technology prioritization*. The lower right, *Integration*, includes *Validation & verification* and *Technology integration*.

Contributions from this research address the following areas:

- Technology integration (linked to RQ1).
- Product architecture in early stages (linked to RQ2).
- Production architecture in early stages (linked to RQ2).
- Technology prioritization (linked to RQ3).

These contributions will be elaborated further in Chapter 5, along with answering of the research questions.

### 2.2.2 LIMITATIONS

The ARC model is used to indicate what *has* been focused on. This means that the areas have been selected above a number of other research areas. Therefore, a number of limitations also exist:

- Little inclusion of the IT-support needed for implementation.
- No inclusion of organizational theory.
- No inclusion of software and electronic design methods.
- Little inclusion of project management literature.

## 2.3 RESEARCH METHODS

Several authors have proposed methods for design research. This research draws on a mix of research methods. The following methods will be described in this chapter:

- Problem-based and Theory-based approach (PbTb).
- Design Research Methodology (DRM).
- Action Research (AR).
- Case Study Research (CS).

A design research methodology can be defined as:

> *"..an approach and set of supporting methods and guidelines to be used as a framework for doing design research."*
>
> (Blessing & Chakrabarti 2009) p. 9

### 2.3.1 PROBLEM-BASED AND THEORY-BASED APPROACH (PBTB)

The first approach contains a description of how research is both problem-based and research-based (Jørgensen 1992). These are based on two fundamental system operations: analysis and synthesis to make up the two fundamental paradigms illustrated in Figure 4.

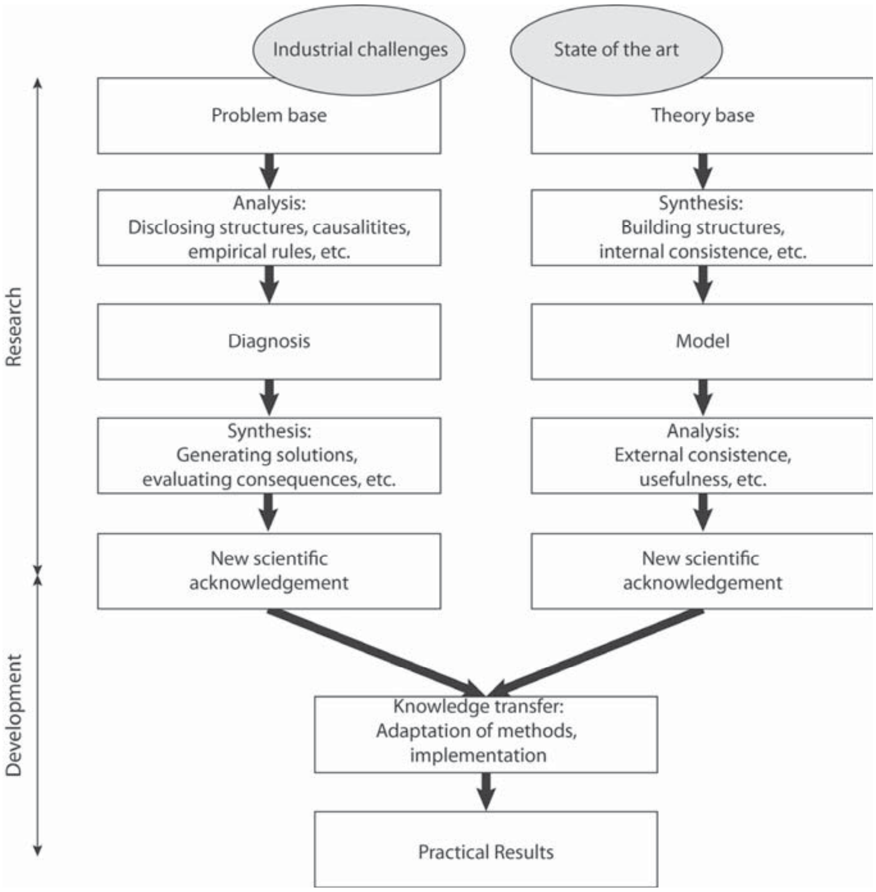


**Figure 4 - Problem-based and Theory-based approach (adapted from Jørgensen 1992)**

The problem-based paradigm is found in participation with projects in industry based on industrial challenges and the theory-based paradigm is found in universities based on state of the art. Jørgensen (1992) emphasizes that the two paradigms should be *combined* within the wholeness of any independent research project. Within the PbTb, no specific data collection methods are mentioned.

### *2.3.2 Design Research Methodology (DRM)*

The DRM framework is a generic design research methodology which links the research questions together and contains suggestions of how to address these in a systematic way. It is focused on supporting engineering and industrial design research (Blessing & Chakrabarti 2009).

The DRM consists of four main stages:

- Research Clarification (RC), where a basis is established for the research to assist in focusing the research project.
- Descriptive Study I (DS-I), where the basis is elaborated by identifying and clarifying in more detail the shortcomings in state of the art. Furthermore, investigation of the phenomenon is initiated with review of empirical research literature, conducting empirical research, and performing reasoning.
- Prescriptive Study I (PS-I), where the support is documented.
- Descriptive Study II (DS-II), where the developed support is evaluated and described with the aim to understand the impact of the support.

The stages in the methodology are not linear, but rather iterative in nature, meaning that the stages can be carried out concurrently or iteratively (Blessing & Chakrabarti 2009). The stages, their relations, the iterative nature, basic means, and main outcomes can be seen in Figure 5.

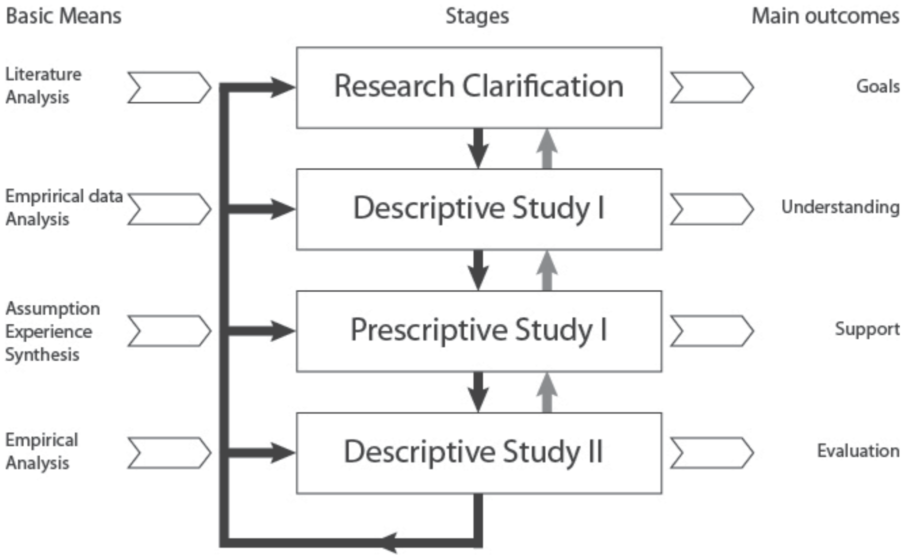


**Figure 5 - DRM (Design Research Methodology) as an overall framework (redrawn from Blessing & Chakrabarti 2009)**

The DRM approach is open to different data collection methods with different methods available at the different stages.

### *2.3.3 ACTION RESEARCH (AR)*

In AR (as illustrated in Figure 6), the researcher enters a real world problem with research themes and takes part in the situation, which enables reflection on the involvement. This leads to findings and new research themes (Checkland & Holwell 1998). Improvement and involvement are central to AR (Robson 2011) and the emphasis is on the participation of the researcher *in* action, which is different from the objective scientist researching *about* action (Coughlan & Coghlan 2002).

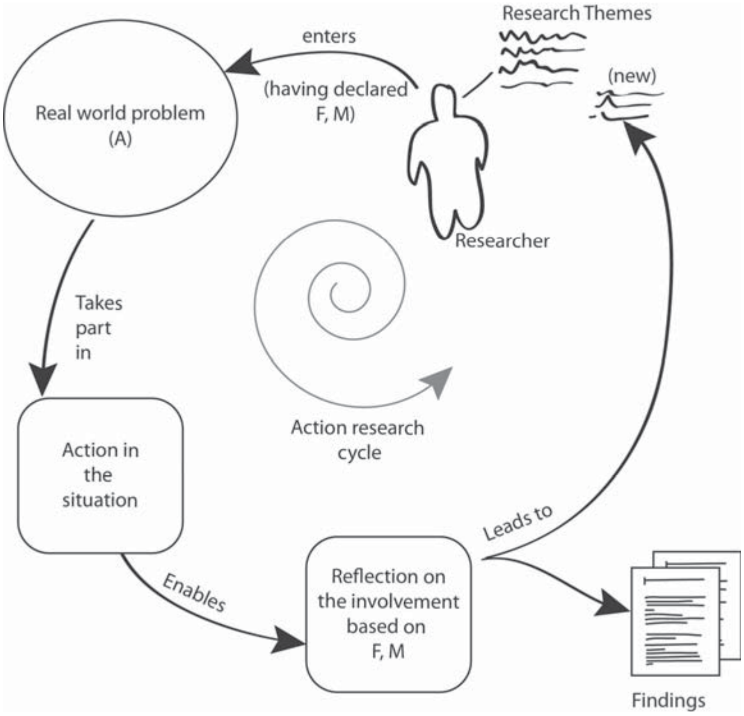


**Figure 6 - Action research (adapted from Checkland & Holwell 1998)**

Similarly, Kemmis and Wilkinson (Kemmis & Wilkinson 1998) describe the AR process as a spiral of cycles of:

- Planning a change.
- Acting and observing the process and consequences of change.
- Reflecting on these processes and consequences, and then,
- Re-planning.

The AR cycle is somewhat comparable to the switching between DS and PS stages in DRM.

### *2.3.4 Case Study Research (CS)*

Case study research is described as a research methodology for a researcher to study a certain phenomenon in order to retain holistic and meaningful effects of real-life events (Yin 2009).

Some of the case study methods allow, just as action research, the researcher to participate. This is particularly true with direct observation and participant observation, although not with as high an interaction as action research. For direct observation and participant observation the following strengths and weaknesses are displayed in Table 1.

**Table 1 - Strengths and weaknesses for direct observations and participant observation (from Yin 2009).**

| Source of evidence | Strengths | Weaknesses |
|---|---|---|
| Direct observations | *Reality* – covers events in real time<br>*Contextual* – covers context of a "case" | *Time-consuming*<br>*Selectivity* – broad coverage difficult without a team of observers<br>*Reflexivity* – event may proceed differently because it is being observed<br>*Cost-hours* needed by human observers |
| Participant observation | *[Same as above for direct observations]*<br>*Insightful* into interpersonal behaviour and motives | *[Same as above for direct observations]*<br>*Bias* due to participant-observer's manipulation of events |

Furthermore, a distinction can be made between case types: single and multi-case design. Single case design is beneficial in, for instance (Yin 2009):

- Critical cases (testing a theory to confirm, challenge, or extend the theory).
- Extreme or unique cases (rare cases that are worth documenting).
- Representative or typical case (circumstances and conditions of a commonplace situation).
- Revelatory case (observing and analyzing phenomenon).
- Longitudinal case (same case at two or more different points in time).

Multi-case design is beneficial in, for instance (Yin 2009):

- Replication (replicating findings in second, third, or further experiments).

The simplest multi-case design consists of two cases. Evidence from multi-case design can be considered more robust (Herriott & Firestone 1983), but rationales from single case designs cannot usually be satisfied by multiple cases (Yin 2009).

### 2.3.5 The Research Method Used in this Research

The research method applied in this research project has been a mix of the presented methods. The parts that have been used from each of the methods have been compiled to create the following method approach:

- The main backbone has been the DRM with the *four research stages*.
- The areas of interest have been crystalized by building relevant *cases* in the DEAP project.
- The cases have been approached differently, in respect to *type*, *data collection method*, and *timespan*.
- The research has been approached from both the *theoretical* as well as *practical side*.
- The researcher has been *participating* in the cases.

The use and correlation between research questions, research stages, research methods and research output are elaborated further in Chapter 2.6.1 and Chapter 2.6.2. The cases are described in Chapter 2.5.1.

## 2.4 Research Evaluation

This section describes the approach to evaluating, i.e. validating and verifying the support developed in this research. Four different validation frameworks have been identified and are presented.

### 2.4.1 *Logic and Acceptance*

Two means of verifying the validity of design theory can be considered (Buur 1990):

Logical verification:

- Consistency: there are no internal conflicts between individual elements of the theory.
- Completeness: all relevant phenomena observed previously can be explained or rejected by the theory.
- Well established and successful methods are in agreement with the theory.
- Cases and specific design problems can be explained by means of the theory.

Verification by acceptance:

- Statements of the theory are acceptable to experienced designers.
- Models and methods derived from the theory are acceptable to experienced designers.

(after Buur 1990)

The two means were proposed in an effort to verify theoretical results empirically. In addition, Buur argues that: "… *verification of design tools is not so much a question of wether they 'work' or not, it is a comparison relative to the qualities of existing tools and working practice."* (Buur 1990, p. 3)

### 2.4.2 *Case Study Validation*

For the purpose of validating case studies the following four types of tactics are used for design tests (Yin 2009):

- Construct validity – used for the identification of the correct operational measures.
- Internal validity – used to establish a causal relationship, whereby certain conditions are believed to lead to other conditions.
- External validity – used for generalization of the findings.
- Reliability – used to demonstrate the repeatability of the study.

The four tests are given to judge the quality of any given research design.

### 2.4.3 *Support Evaluation*

When evaluating the support developed through research, three central points can be used (Blessing & Chakrabarti 2009):

- Usability: Can the support be used?
- Applicability: Does the support address the factors it is supposed to?
- Usefulness: Are the factors affected as expected?

Blessing and Chakrabarti (Blessing & Chakrabarti 2009) state that the actual support may differ from the intended support in: implementation, medium, functionality, domain coverage, and performance, and furthermore underline that evaluating design support is essential.

### 2.4.4 *Validation Square*

The Validation Square (Pedersen et al. 2000) is a two-by-two for structural validation and performance validation, as illustrated in Figure 7.

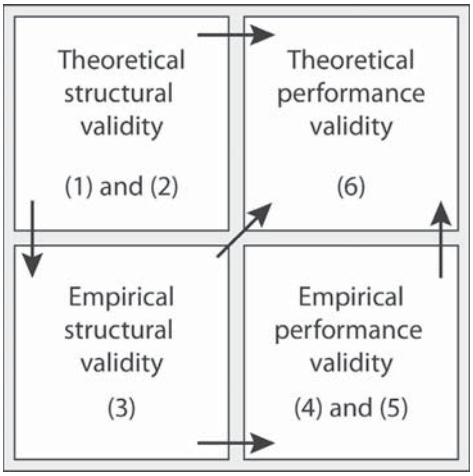


**Figure 7 - Validation square (redrawn from Pedersen et al. 2000)**

Structural validation:

(1) Accepting the individual constructs of the method.
(2) Accepting the internal consistency of the way the constructs are put together in the method.
(3) Accepting the appropriateness of the example problems that will be used to verify the performance of the method.

Performance validation:

(4) Accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem(s).
(5) Accepting that the achieved usefulness is linked to applying the method.
(6) Accepting that the usefulness of the method is beyond the case studies.

after Pedersen et al. (2000)

Step six is used to build confidence in generality, comparable to the external validity in the case study validation.

### 2.4.5 *Evaluation of this Research*

Summing up, different approaches to research evaluation can be used, each with their rationale. A number of support tools have been developed during the PhD project and tested in an industrial setting.

The validation square combines many of the points from the other validation frameworks, into a six-part validation. Therefore, the validation square has been chosen for validation of the research in Chapter 6.

## 2.5 Research Planning

The research project followed the DEAP project from primo July 2012 to ultimo April 2015. The research presented in this thesis was conducted during this period. To gain a better overview of the interaction of the research in the DEAP project, a decomposition of the work areas is presented here as separate cases. Furthermore, the research stages as well as research exchange is presented in this chapter.

### *2.5.1 Cases*

In the DEAP project, a number of cases were used as a basis for this research (see Table 2).

The duration of the cases ranged from 2 months to 30 months. Cases 4-7 were followed over a period of 30 months with different levels of interaction.

The common denominators for the cases were:

- All cases were related to the IFD project.
- Cases 2-3 were concurrent development tracks of transducer design and transducer production.
- Cases 4-7 were concurrent development tracks of different technology prototypes.

Most of the cases were run concurrently. Therefore, the researcher balanced the attendance in the cases according to the needs of the project in terms of milestones, deliveries and meetings. The work packages noted in Table 2 refer to sub-projects in the DEAP project. Those are described in Chapter 4.

**Table 2 - Overview of the cases**

| Icon | # | Case | Description | Work package | RQs | Duration |
|---|---|---|---|---|---|---|
|  | 1 | Progress Reporting | Data analysis of 138 monthly reports | WP 0, WP 6, WP 7, WP 8, WP 9 | RQ1 | 2 months |
|  | 2 | Element Design | Case Study of platform definition | WP 3 | RQ2 | 2 months |
|  | 3 | Film Production | Case Study of Production architecture definition, early phases | WP 2 | RQ2 | 6 months |
|  | 4 | Incremental Motor | Prototype A | WP 6 + WP 4 | RQ1 | 30 months |
|  | 5 | Wave Energy Harvesting | Prototype B | WP 7 + WP 4 | RQ1 | 30 months |
|  | 6 | Heating Valve | Prototype C | WP 8 + WP 4 | RQ1 | 30 months |
|  | 7 | Loudspeaker | Prototype D | WP 9 + WP 4 | RQ1 | 30 months |
|  | 8 | Prioritization | Identification of critical technology building blocks | WP 0, WP 1, WP 2, WP 3, WP 6, WP 7, WP 8, WP 9 | RQ3 | 6 months |

### 2.5.2 RESEARCH STAGES

The main process of the research followed the DRM four-stage approach. The link between overall topic, research questions, research stage, and academic output is illustrated in Figure 8.

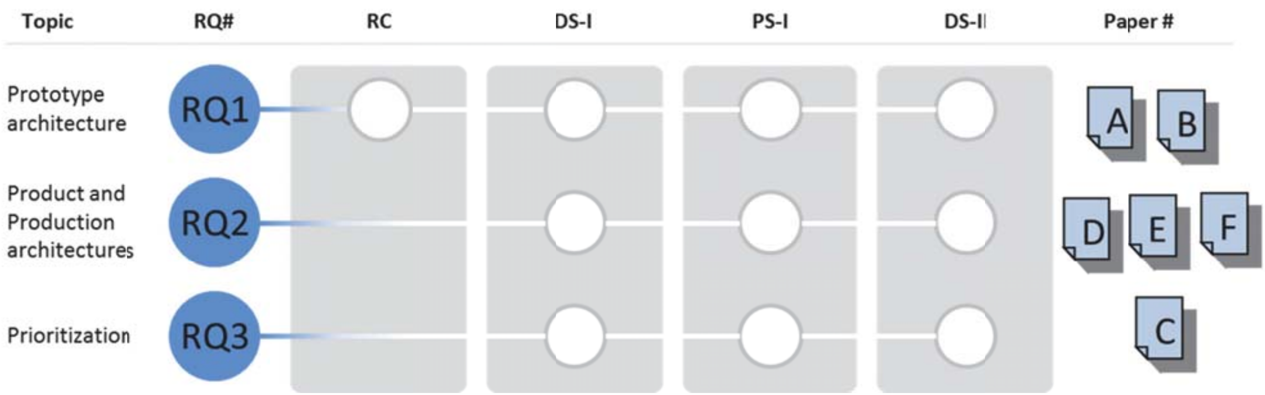


**Figure 8 - Relating Topic, RQ's, Research stages, and Papers.**

The produced papers in the majority of the cases cover the stages DS-I, PS-I, and DS-II. The RC stage was used to clarify the context of the research. The initial understanding of the context was built with initial pointers towards problem areas. The DS-I stages were used to gain a comprehensive, in-depth knowledge about the problem situation. Through this phase, project participation in the DEAP project, the conducted interviews and document analysis from Case 1 in Table 2 supported in-depth literature studies. The PS-I stages were used for building the support tools as well as used in the DEAP project. Multiple action research cycles were performed in cases 4-7. The DS-II stage was used to describe the outcome of the developed support tools. The support tools were tested and the outcomes recorded. Mainly qualitative data was collected.

### 2.5.3 DATA SOURCES IN THE CASE PROJECT

The data obtained in this project has predominantly been qualitative. The primary sources for the research were, as described from Yin (Yin 2009):

- Participatory observation.
  - Participation in daily work.
  - Participation in more than 100 meeting activities.
    - Teleconferences with and without virtual screen-sharing.
    - Workshops.
    - Work meetings.
- Semi-structured interviews with project participants.
- Documents.
  - Monthly reports.
  - Test reports.
  - Work documents.

In addition, a number of interviews were made with individuals inside and outside the DEAP project. These were:

- The Head of Department of New Technologies in a global medico company.
- A Group Manager in a Solid Oxide Cell technology for Electrolysis (SOEC technology) company.
- A Director of an engineering consultancy section and Entrepreneur with more than 20 years of experience.
- A Professor of Automation with more than 10 years of experience.
- A Lecturer in Mechatronics.

The purpose of these interviews was to add to the PS-1 of this research. The interviewees were taken from different contexts to give a balanced view on technology development.

### *2.5.4 Role of the Researcher*

The participation of the researcher in the DEAP project was in the role of process consultant, "*to work in a facilitative manner to help the clients inquire into their own issues and create and implement solutions*." (Coughlan & Coghlan 2002).

During the three years affiliated to the DEAP project, access was given to a variety of data sources: full access to the data repository of the DEAP project, access to relevant meetings, such as Work Package meetings, monthly meetings, project symposia, and steering committee meeting. The data used in the research, mainly stemming from the DEAP project, was predominantly qualitative in nature.

Being part of the project management work package and working in close collaboration with the Project Manager provided a unique opportunity for sparring as to reflections on meetings and observations in the project.

A variety of tasks were carried out as part of the project management team. The researcher was mainly responsible for the architecture work in the application work packages and participated in weekly meetings. The architecture work exploited the virtual setup of the project especially in meetings held online, where architecture work was done on-the-fly as part of the meetings.

The researcher supported the DEAP film production with the formulation of product architecture overviews as a main driver towards DEAP project symposia.

In the concluding phases of the project, an effort was made to support the project end debriefing and build a tool for identifying and prioritizing critical technology areas for future development.

### *2.5.5 Research Exchange*

Central parts of a PhD-study are research as well as the educational intent of training the PhD-student in the art of research. This section describes the educational part.

**Research training**

Courses with a workload equivalent to 30 ECTS points have been completed during the PhD study. A majority of the courses were intentionally sought abroad to create a research network at the same time as gaining knowledge within specific topics.

**Courses and schools**

- *Platforms and Technology* (Special Course).
  - Held at Technical University of Denmark (DTU). Literature study of the two subjects.
- *ISSPAD 2014* (International Summer School on Product Architecture Design).
  - Held at Technical University of Hamburg-Harburg (TUHH). Focus was on advancements within product architecture design and product architecture modeling.
- *Design Research Terms and Methods for PhD Students* (Special course).
  - Held at Technical University of Denmark (DTU). Discussion of terms and research dissection.
- *Research Methods for Engineering Design Research: Data Collection, Analysis and Evaluation* (Course 42704).
  - Held at Technical University of Denmark (DTU). Discussing and hands-on working with design research methods.
- *How to Write a Scientific Paper* (Course 11621).
  - Held at Technical University of Denmark (DTU). Focused on increasing skills within academic writing as well as the review answer process.
- *SSEDR 2013* (Summer School on Engineering Design Research).
  - Held in Samobor, Croatia, arranged by the Technical University of Zagreb (Week 1), and Heyda, Germany, arranged by the Technical University of Ilmenau (Week 2). Focused on engineering design research to improve the research structure and basis, such as research questions.
- *IS3E 2013* (1st International Spring School Systems Engineering).
  - Held at University of Paderborn. Focused on gaining a better insight into Systems Engineering.

**Participation in conferences, seminars and workshops**

The author has participated in the following conferences, seminars and workshops:

- *20th International Conference on Engineering Design*, ICED15, July, 2015, Italy (Paper and oral presentation).
- *DNATF DEAP Symposium 4*, held at Technical University of Denmark, April, 2015.
- *DNATF DEAP Symposium 3*, held at Danfoss, Nordborg, Denmark, 2014.
- *13th International Design Conference*, DESIGN 2014, Dubrovnik, Croatia, 2014, (Paper and oral presentation).
- *Product Development Day*, Industrial seminar held at the Technical University of Denmark, 2013.
- *DNATF DEAP Symposium 2*, held at Aalborg University, Denmark, 2013.
- *Radical Simplification by Design*, Industrial seminar held at Danish Design Center, Denmark, 2012.
- *DEAP Workshop*, 2-day workshop held in Sorø, Denmark, 2012.
- *Product Development Day*, Industrial seminar held at the Technical University of Denmark, 2012.
- *DNATF DEAP Symposium 1*, held at Technical University of Denmark, 2012.

Attending conferences has given insight into the main research field of the PhD project. Skills and experience in writing, reasoning and presenting academic material have been obtained.
For the oral presentations, slideshows have been used for exchange of knowledge with researchers within the field (Figure 9).

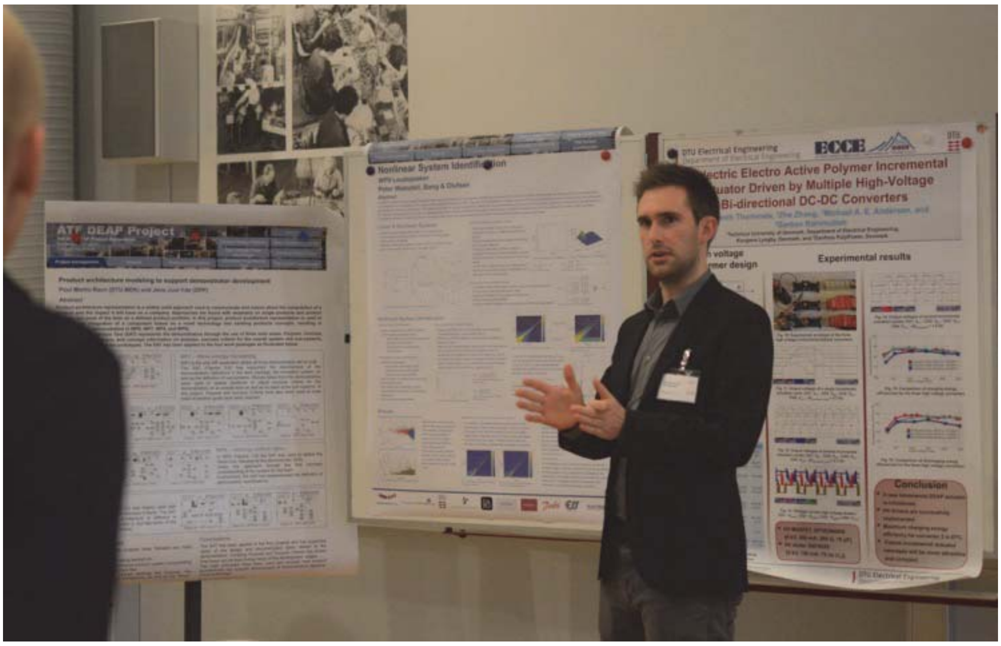


**Figure 9 - Oral presentation of architecture work, DEAP Project symposium 2014. [Photo: Tómas V. Guðlaugsson]**

Posters have been used intensively throughout the period of the PhD project as a means to communicate and discuss the research (Figure 10).

**Figure 10 - Poster work during a Danfoss PolyPower workshop. [Photo: Tómas V. Guðlaugsson]**

### Teaching

During the PhD project, the author has taken part in multiple teaching activities at the Technical University of Denmark, both graduate and under-graduate level courses.

Teaching activities (as compulsory work) have been carried out on two courses:

- *Technology Platforms and Architectures* (graduate level, spring 2013 & 2014).
- *Product Design and Documentation* (under-graduate level, fall 2012 & 2013).

Additionally, guest lectures have been given to increase presentation and teaching skills:

- *Visual Communication* (under-graduate level, 2012 - 2015).

### Peer-reviews

As part of publishing academic work, a number of peer-reviews as referee have been made for different academic instances.

- *Journal of Concurrent Engineering, Research and Applications* (2015).
- *Nord Design* Conference (2014).

Apart from peer reviews, theses of finishing PhD students have been reviewed during the PhD study to gain insight into the different research areas in the Section of Engineering Design and Product Development, as well as to provide inputs and corrections to the manuscripts.

*"Theory without practice is empty, practice without theory is blind."* [Translated from German]
- (Maser 1976)

# 3 Theoretical Base

*The purpose of Chapter 3 of the thesis is to introduce the theoretical base for the research.*

*Four areas make up the theoretical base: Systems, Technology, Integration, and Architectures and Platforms.*

## 3.1 Introduction of Theoretical Base

The theoretical basis for this research has drawn from the following main contributing areas for understanding:

- *Systems* – introduces theories and models to understand systems within engineering design.
- *Technology* – introduces theories and models of the phenomenon of technology.
- *Integration* – introduces theories and models about integration, and especially, integration of novel technology.
- *Architecture and platform* – this chapter introduces theories and models on architectures and platforms.

The above topics have each been studied during the course of the PhD project. Other theories have also been studied but do not form the basis and are not included in the following sub-chapters. The chapter is influenced by the research of multiple researchers from the Section of Engineering Design and Product Development at the Technical University of Denmark. The reason for this is the strong theory contribution tradition.

For each sub-chapter, a summary is given of how previous research contributes to the research of this PhD project.

## 3.2 Understanding Systems

Building an understanding of a system is deeply anchored in most sciences. The understanding of systems in this research is based on system theories originating from mechanical engineering.

### *3.2.1 Systems in General*

A system has structure, i.e. elements and relations (Hubka & Eder 1988). This has been articulated by many authors; however, within Engineering Design a model of a system in general can be found as illustrated in Figure 11.

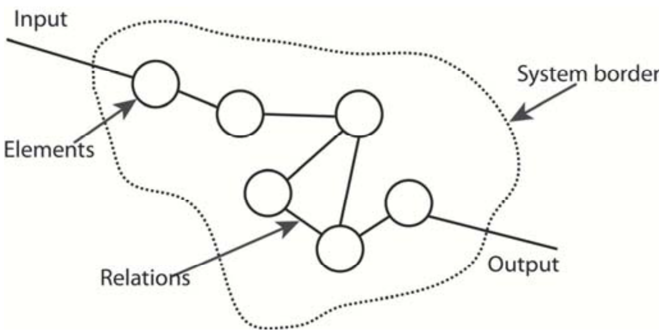


**Figure 11 - Model of system in general (redrawn from Hubka & Eder 1988)**

Here, a system is made up of elements and relations with a defined boundary (the system border). When the system is given an input (stimuli), an output (response) is created. The system itself can be viewed through a model capturing the relevant entities and relations based on a certain view. Andreasen argues that the perception can be based on the following: object + viewpoint -> system (Andreasen 1980).

> *"A **system** is a model of an object (a real or conceived product or activity) based on a certain viewpoint, which defines the elements of the system and their relations. A system carries **structure**, i.e. the elements and their relations (arrangement, architecture) and **behaviour**, i.e. the system's response to a stimulus depending on stimuli, structure, and state."*
>
> (Andreasen et al. 2015) p. 198

Andreasen (Andreasen 2011) proposed that the attributes of a system could be articulated as:

- *Characteristics* – structural attribute, that defines the system with respect to the structure, elements and relations of what the system *is.*
- *Properties* – behavioural attribute that describes the response of the system upon stimuli, but in relation to the surroundings of what the system *does.*

Weber (Weber 2014) added to the attributes in that characteristics (such as parts structure, shape, dimensions, materials and surfaces) *can* be directly influenced by the engineer/designer, while behaviour (such as function, safety, and reliability) *cannot* be directly influenced by the engineer/designer.

For the understanding of the different research areas which apply systems and in what area this research is conducted, a distinction between different systems can be made. Hubka and Eder (Hubka & Eder 1988) proposed the hierarchy found in Figure 12.

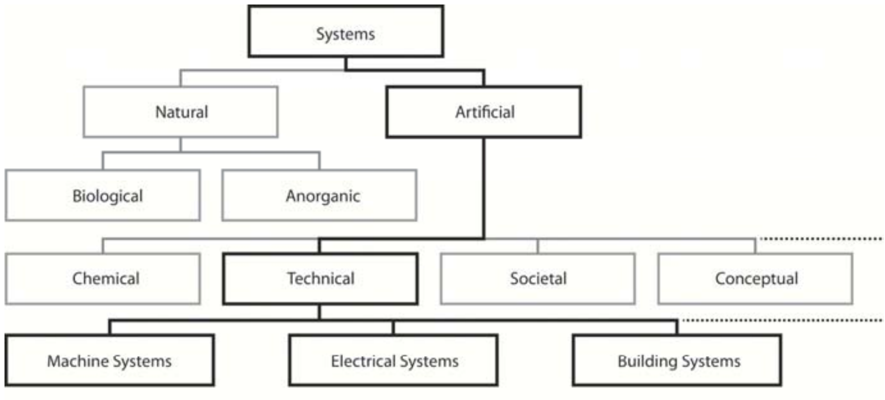


**Figure 12 - Different system types (adapted from Hubka & Eder 1988)**

This research is focusing on technical systems which are a sub-type of artificial systems. Technical systems cover a wide variety of systems affected by engineering.

### 3.2.2 *THEORY OF TECHNICAL SYSTEMS*

The Theory of Technical Systems was introduced by Hubka and Eder (Hubka & Eder 1988) and aims to:

> *" - Describe and classify the principles of action of technical systems,*
> *and their properties and characteristics,*
> *- to build up a basic terminology as a foundation for a study of engineering design, and*
> *- to formulate important perceptions about technical systems on which to*
> *base further study of Engineering Design,…"*
>
> (Hubka & Eder 1988) p.V

It is argued to be an *"...ideal "advanced organizer" for explaining technology and its role in society,...*" (Hubka & Eder 1988, p. 228). A central concept used throughout the theory is the notion of transformation, where an operand is transformed in a transformation system by a transformation process. This transformation process is executed by an execution system that comprises a human system and a technical system (see Figure 13).

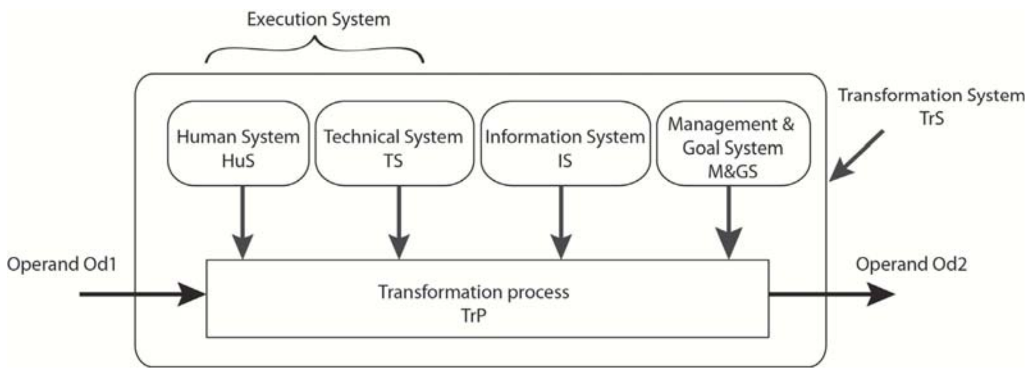


**Figure 13 - The transformation process from TTS (redrawn from Hubka & Eder 1988)**

In addition, a Model of Technical Systems (TS Model) is defined, in which four domains each present an abstraction level: transformation, function, organ, and component.

**How systems contribute to this research**
An understanding of systems has contributed to this research with a basic understanding of what a system is composed of, how TS can be modeled, as well as the basic constituents of a system: characteristics and properties. The perception of systems is used particularly in the Papers B, C, E, and F.

### *3.2.3 Understanding Domains*

Based on TTS, Andreasen (Andreasen 1980) proposed the Theory of Domains. In ToD, initially four domains were proposed to describe the elements of a TS: process, function, organ, and parts (Andreasen 2011). Later, the domains were revised to encompass the domains: activity, organ, and part (see Figure 14).

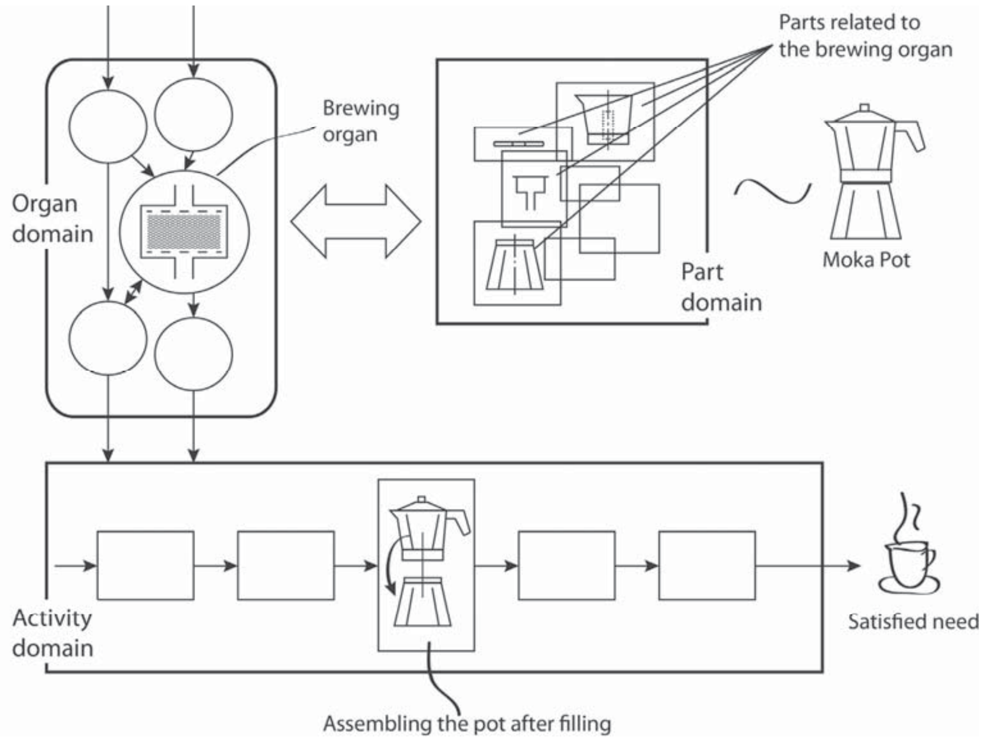


**Figure 14 - The three domains from the Domain Theory (redrawn from** (Andreasen et al. 2015)**)**

The activity domain describes how the product is *used*. Here, core characteristics of the activity are described: the operands that are changed, the necessary effects from the operators and the relations to the operands, and the conditions of the necessary surroundings (Andreasen et al. 2014).

The organ domain describes how the product *functions*. Here, the central entities are the organs that interact with each other. In the organ domain the description of how an organ composition leads from the inputs to the effects needed for the transformation activity (Andreasen et al. 2014).

> *"An organ is a function element (or 'means') of a product, displaying a mode of action and a behaviour, which realise its function and carry its properties."*
>
> (Andreasen et al. 2014), p. 179

The part domain describes how the product is *built up*. The central entities are parts. These are defined by requirements from the organ structure. The characteristics of the parts are similar to that of Hubka and Eder (Hubka & Eder 1988), i.e. form, material, surface quality, and dimension (but leaving out state) (Andreasen et al. 2014).

The three domains each represent a system view that can be modeled. The domains can be explored as part of product synthesis, i.e. determination of a product. This can be done either in an inter-domain or intra-domain manner. Andreasen et al. (Andreasen et al. 2015) argue that the three domain progression represents a good understanding of product synthesis.

**How domains contribute to this research**

The understanding of domains has contributed to this research in a number of ways. Firstly, the understanding of different domain-views has been used to gain an understanding of the view with which one can look upon a system. Secondly, the notion of organs has illustrated how a functional view can be applied to gain an understanding of the main interactions in a system. Lastly, the three domains have been used in the understanding of synthesis. The perception of organs is used particularly in Papers B and E.

### *3.2.4 Understanding Modeling*

Duffy and Andreasen (Duffy & Andreasen 1995) described a basic philosophy of how modeling approaches could be classified. The main notion is that all models are built based on the reality. Reality is captured in a phenomenon model through observations and analysis. From the phenomenon model, an information model can be formulated that can be implemented in a computer model (Andreasen 2009) (see Figure 15).

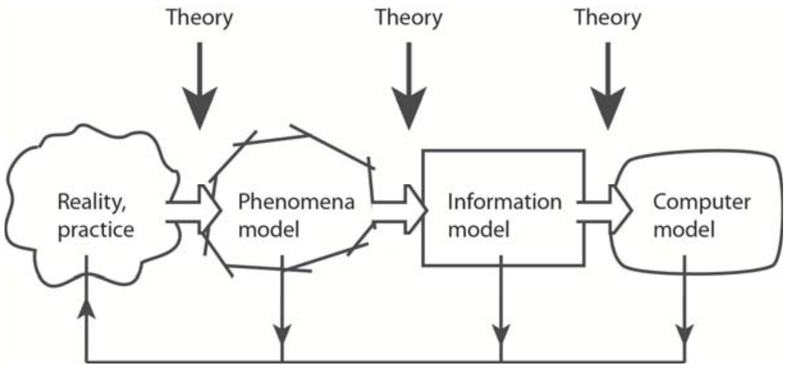


**Figure 15 - Modeling systems (redrawn from Duffy & Andreasen 1995)**

Linking a model to the process of modelling, the following four characteristics of the model process are found: *object*, *property*, *purpose*, and *user* (Andreasen 1994). Additionally, the characteristics of the model are the *code* and the *medium*.

> *"A model is a simplified and therefore to a certain extent a fictional idealised representation."*
>
> (Maier et al. 2014) p. 133

**How modeling contributes to this research**

Understanding modeling has contributed to this research through understanding the difference between model types. Upon describing the reality, the characteristics of both the modeling process and the model has to be taken into account. Furthermore, the understanding of a model being only an idealised representation has helped with cutting to the bone in the models presented in this research.

## 3.3 Understanding Technology

Understanding technology is a key aspect of this thesis as the research was done in a technology development context. Here, the nature of technology, life-span of a technology, development of a technology, and measurement of technology will be touched upon.

### *3.3.1 Nature of Technology*

Technology is used as a key point in many research areas. Researchers use it for instance to explain new knowledge about principles brought into product development or production development (Schulz et al. 2000), as a basis for product platforms (Meyer & Lehnerd 1997) and even representations for a platform itself (Levandowski et al. 2012).

However, as a starting point in the understanding of use technology, the following understanding, based on phenomena can be used:

> *"…technology is a phenomenon captured and put to use."*
>
> (Arthur 2009) p. 51

Arthur argues that phenomena are natural effects and have no use attached to them, and that:

> *"To understand a technology means to understand its principle, and how this translates into a working architecture."*
>
> (Arthur 2009) p.35

Here, principle is the idea of use of a phenomenon for some purpose. This leads to understanding that connected to a technology is a *use*.

Hubka and Eder (Hubka & Eder 1988) describe technology as *"the sum of all those real and potential processes occurring in the world which are influenced by human beings."* (p. 13.), linking technology to processes. However, it is specified as "*applying effectors (tools) to situations to produce change."* (Hubka & Eder 1988) p. 16.

In an industrial context, technology has also been illustrated with a link to the different life-phase systems of a product (in an example of a welding machine):

> *"Any product involves several technologies, partly in itself (product technology), and partly its various life phase systems (production technology, distribution technology, service technology, etc.)"*
>
> (Mørup 1993) p. 201

Coupled to this statement is also an example of aluminum extrusion technology (see Figure 16). Here, the two other parts of technology are identified: the extruded profile in the product (relating to the product technology), and the extrusion process itself (relating to the production technology).

Product technology is thus related to the product itself. Production technology is related to the realization of the physical entities that make up the product and new designs are built on known technologies, often with the existence of production technologies as a precondition (Arthur 2009). Some authors argue that production technology is an enabler of product technology (Schulz et al. 2000).

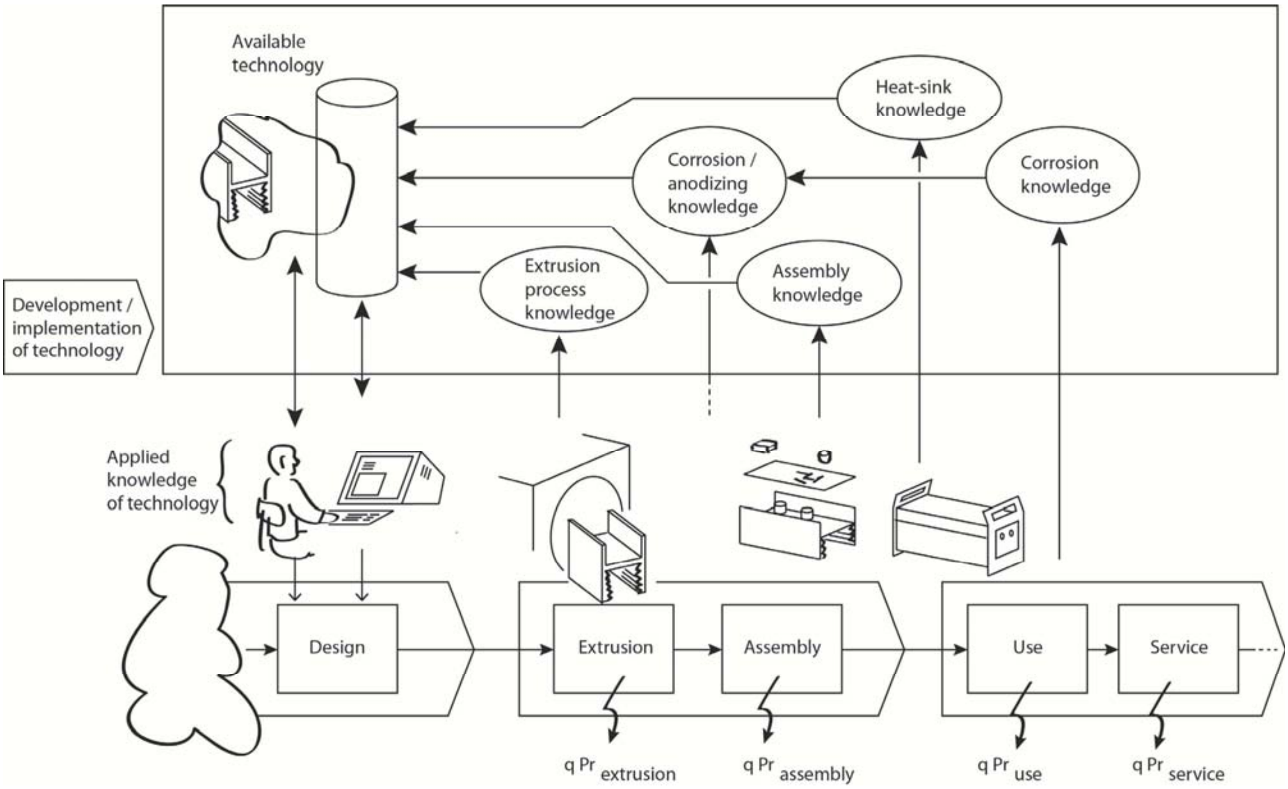


**Figure 16 - Example of technology knowledge (redrawn from Mørup 1993)**

Andreasen, Hansen and Cash (Andreasen et al. 2015) describe how technology can be seen in the relation to use and product: "*A technology is the sum or interaction between a product, the activity, and its result.*" (p. 203).

**How general technology understanding contributes to this research**
A general understanding of the nature of technology has contributed to this research as a central term. Especially an understanding of the three interwoven parts of technology has been beneficial for understanding the structure of the industrial project and the impact on a company.

### 3.3.2 *LIFE-SPAN OF A TECHNOLOGY*
Observing a relation between technologies and time in a plot described as an S-curve, has gained wide acceptance. The S-curve describes the life-cycle of a technology, in two axes: technical performance and research effort (see Figure 17a).

In the early stages of a technology, performance progression is slow. When the technology is better understood, the rate of technological improvement increases. In the mature stages, the technology will approach a natural or physical limit (Foster 1985; Christensen 2009a; Arthur 2009).

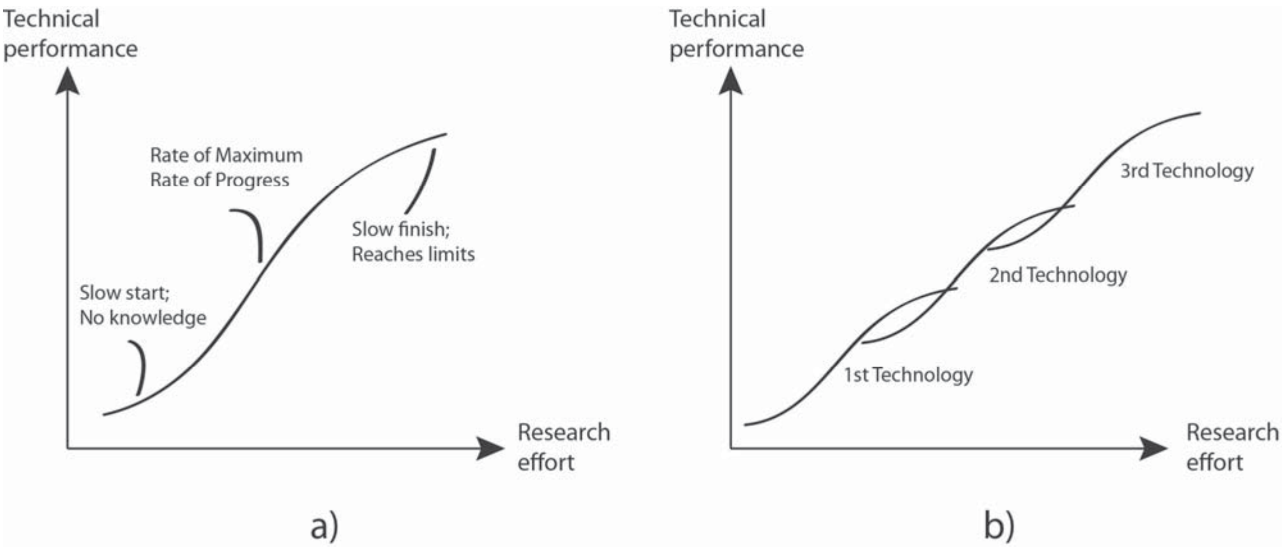


**Figure 17 - a) General technology s-curve b) technology generations (redrawn from Foster 1985; Christensen 2009b)**

However, plotting other, or new, disrupting technologies provides a depiction of the life-transitions of technologies as one generation of technology can overtake the other. The depiction in Figure 17b can be used for both descriptive (provide insights to potential or alternative technologies at industry level) and prescriptive (guiding strategic management) studies (Christensen 2009a).

When a new technology is offered to the market it is in its early stages and often found to perform worse than the previous generation (Schulz et al. 2000). However, the general tendency is a gradual transition to the new technology as its performance is increased (Christensen 2009b). The initial performance limitation may be improved through superior parts and structural deepening (Arthur 2009).

**How life-span of a technology contributes to this research**
Understanding life-spans of technology has contributed to this thesis with the understanding of how novel technologies may affect previous generations of technology.

### 3.3.3 DEVELOPMENT OF TECHNOLOGY

Developing technology, or building knowledge about technology, is in the industry widely accepted in the organizational structure as a separate department entity as illustrated by e.g. Nobelius (Nobelius 2002) (see Figure 18).

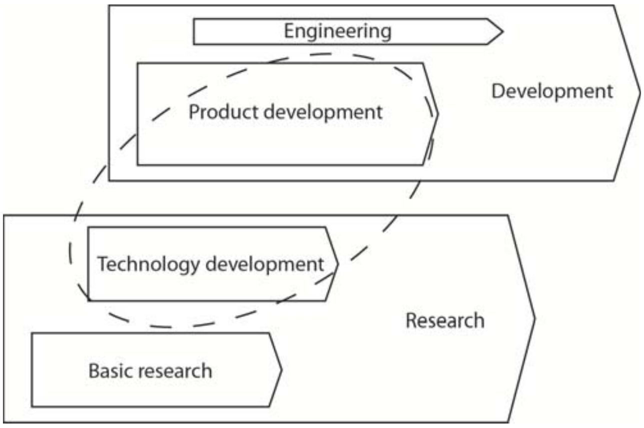


**Figure 18 - The separation of technology development and product development (adapted from Nobelius 2002)**

The split of the two has resulted in a transfer of technology to be a prominent managerial issue (Nobelius 2004). In order to understand what is meant by technology development, the following can be stated:

> *"… a directed effort at developing new "knowledge, skills and artefacts" that, in turn, will facilitate product/process development…"*
>
> (Högman & Johannesson 2013) p. 265

In order to describe the transfer between technology development and product development, Schultz et al. (Schulz et al. 2000) describe how product development is "fishing out" appropriate technologies from the technology development.

For controlling the process of technology development only a few models have been found:

- Cooper (Cooper 2006) adapted the Stage-Gate model (Cooper 1990) to fit technology development, consisting of three stages and four gates. Each gate is a go/kill decision and the last gate hands over the technology to e.g. New Product Development (NPD).
- Högman and Johannesson (Högman & Johannesson 2010) proposed a model based on the Stage-Gate approach. The model linked the Stage-Gate to technology readiness levels (TRL) with six Stages and six Gates (TRL is discussed in Chapter 3.3.4). Within each Stage, a process was proposed, adding up to six iterations through the model before hand-over to product/process development.
- Cohen et al. (Cohen et al. 1998) proposed the ERE Stage-Gate system on the same basis and added two stages (Stage A and Stage B) prior to the regular Stage-Gate model. Nine key success dimensions are introduced for assessment during the process.
- Ajamin and Koen (Ajamian & Koen 2002) introduced the TechSG process and argued "*you know only what you are going to do next, not how it is going to turn out. So you cannot plan*

*subsequent actions in great detail.*" (p. 270). Based on this, they argue that the technology development team can only see to the next gate.

Despite the few development models, the general goals of development are to reduce the risk related to the technology while increasing the performance and maturity of the technology (see Figure 19).

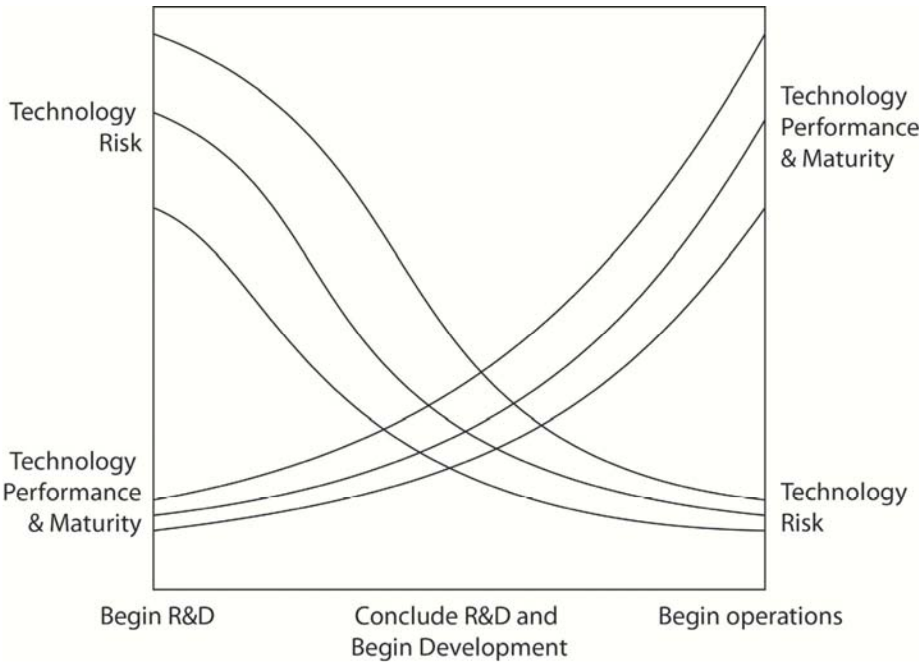


**Figure 19 - Factors in maturing a technology (redrawn from Mankins 2009a)**

Until sufficient performance or robustness has been obtained the technology will not be ready for inclusion in the product development.

Mankins (Mankins 2009a) adds that *"the critical point, of course, is that at which a decision must be made as to whether the technologies needed for a new system have collectively reached the point of maturity, risk and performance at which system development can proceed"* (p. 1209).

**How development of technology contributes to this research**
While only few technology models can be found, developing technology is essentially about decreasing technology risk and increasing technology performance and maturity, as well as knowledge about the technology.

### *3.3.4 Measurement of Technology*

In order to measure technology, a main classification can be made for a given technology to:

> *"▪ deliver its function (Technology Readiness)*
> *▪ be produced (Manufacturing Readiness)"*
>
> (Williamson & Beasley 2011) p. 3

Mankins (Mankins 2009a; Mankins 2009b) provided the assessment metrics Technology Readiness Levels (TRL), Technology Need Value (TNV), and R&D[3] (R&D Degree of Difficulty) in a readiness and risk assessment approach for technology. These are all multi-level assessment metrics used to assess the risk in development. The TRL metric has been used in National Aeronautics and Space Administration (NASA) since the 1970s (Mankins 2009b). Similarly, a technology readiness method has been introduced to "… produce a documented state of technological stability" ((Clausing & Holmes 2010) p.53). It has been argued in literature that TRL does not allow assessment of maturity at a system level (Mankins 2009a). Therefore, Integration Readiness Level (IRL) and System Readiness Level (SRL) were introduced (Sauser et al. 2010; Sauser et al. 2008). An overview of different assessment metrics can be seen in Table 3.

**Table 3 - Different technology assessment metrics (technology and manufacturing)**

| Abbreviation | Metric | Source |
|---|---|---|
| TRL | Technology Readiness Level | (Mankins 2009b) |
| TNV | Technology Need Value | (Mankins 2009a) |
| R&D[3] | Research Development Degree of Difficulty | (Mankins 2009a) |
| IRL | Integration Readiness Level | (Sauser et al. 2010) |
| SRL | System Readiness Level | (Sauser et al. 2008) |
| TRA | Technology Risk Assessment | (Clausing & Holmes 2010) |
| MRL | Manufacturing Readiness Level | (OSD Manufacturing Technology Program 2015) |
| MCRL | Manufacturing Capability Readiness Level | (Ward et al. 2012) |

While the technology assessments often are used in a product-related context, assessment methods can also be found tailored for processes or in manufacturing–related contexts. The United States Department of Defence (DoD) has used Manufacturing Readiness Level (MRL) to assess manufacturing risk (OSD Manufacturing Technology Program 2015). Different variations can be found, e.g. a version directly linked to the nine TRL levels, the Manufacturing Capability Readiness Level (MCRL) (Ward et al. 2012).

**How measuring technology contributes to this research**

The measuring of technology has contributed to this research in understanding a documented maturity of a given technology in a development context. This has been used especially in Paper C.

## 3.4 Understanding Integration

When composing systems, systems integration is referred to as the process by which the system's elements are brought together in a whole.

### *3.4.1 Composition and Decomposition*

Integration is linked to the composition of a system. However, there can be no composition without decomposition. Many of the engineering design methodologies deal with decomposition and composition of the system or product under development. A number of these follow the process of decomposition of e.g. problems, functions, user actions, customer needs, effects, etc. (Ulrich & Eppinger 2008; Hubka & Eder 1988).

Cross (Cross 2000) presented a model in which the two different patterns of problem and solution decomposition are touched upon. He put emphasis on the separation of the two and the understanding of the mapping between them, as illustrated in Figure 20.

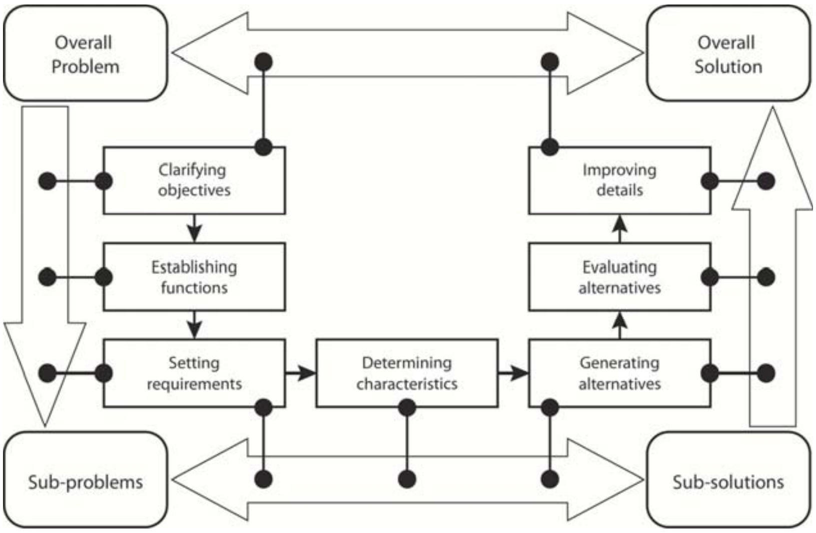


**Figure 20 - The symmetrical problem/solution model (redrawn from Cross 2000)**

The decomposition and composition pattern is a part of the progressive concretization and detailing of product synthesis (Svendsen 1994).

**How composition and decomposition contributes to this research**
Bringing together a system is a part of the product synthesis. While decomposition has to do with splitting into smaller, composition has to do with the bringing together in a whole.

### *3.4.2 Integration Process*

In Systems Engineering (SE) integration is seen as a process in itself and includes activities to plan and perform integration (INCOSE 2011):

- Plan integration.
    - Define the integration strategy.
    - Schedule integration testing tools and facilities.
- Perform integration.
    - Assemble system elements according to integration plan.
    - Validate and verify interfaces – confirm correct flow of information across internal interfaces through "black box testing" at each successive level of assembly.
    - Document integration testing and analysis results.
    - Document and control the architectural baseline – includes capturing any modifications required during this process.

> *"The purpose of the Integration Process is to assemble a system that is consistent with the architectural design. This process combines system elements to form complete and partial system configurations in order to create a product specified in the system requirements."*
>
> (ISO/IEC/IEEE International Standard 2008) p. 44

In the V-model, see Figure 21, system integration is a distinct phase on the right side of the model used to validate (Are we building the right thing?) and verify (Are we building the thing right?) the system in question (INCOSE 2011). On the left side of the model system decomposition and product design is performed.

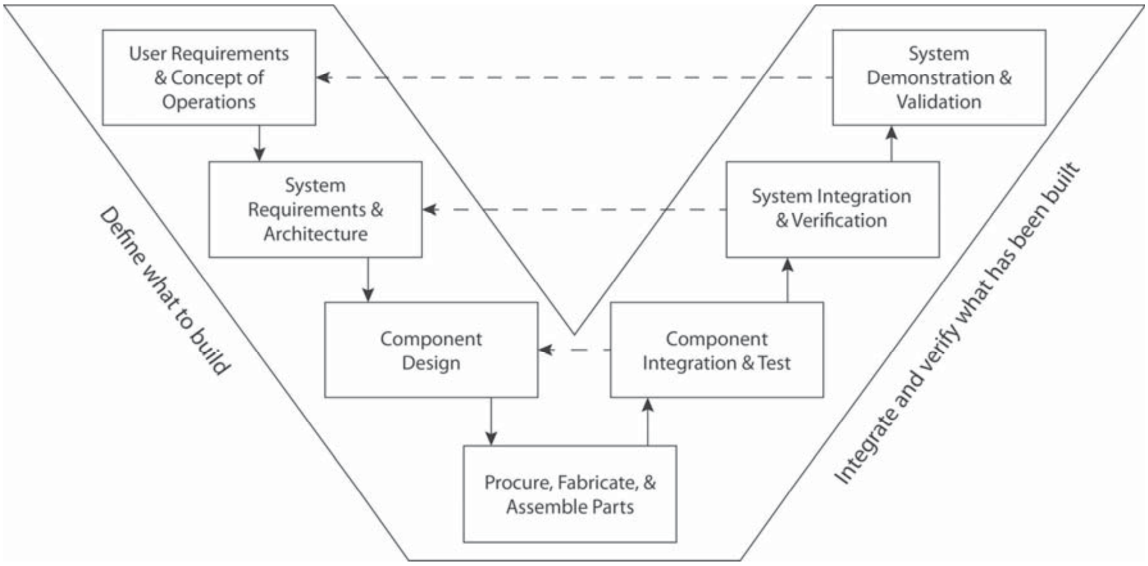


**Figure 21 - V model (redrawn from (Sauser et al. 2010))**

However, the integration starts in the early stages as tests are dependent on the system composition.

Grady (Grady 1994) argues that "*integration excellence can be claimed when: (1) it has been proven that the product articles perfectly satisfy the requirements for which they were designed, (2) that they perfectly reflect the controlling documentation, and (3) that we have completed these feats within budget and schedule limitations.*" (p. 231).

**How integration process contributes to this research**

The integration process is a process to combine system elements to a product. The integration process has been a part of the hind-lying skeleton of this research.

### 3.4.3 *Integration of Technology*

When integrating a novel technology into a product, changes will happen in the product design. For integration of technology, two aspects can be taken into consideration:

- Integration of knowledge (with reference to the understanding of technology in Chapter 3.3.1).
- Integration of a certain structure or device, based on the technology (with reference to Chapter 3.4.1 and 3.4.2).

The first, integration of knowledge, can be understood through literature linking to *knowledge* and *capabilities* (Schulz et al. 2000; Iansiti 1995). Those can be tied to individuals and organizations learning about a technology that is either new to the company or new to the world.

Even though a technology can be taught and learned, Nieto (Nieto 2004) argues that "*Most technological knowledge has a large tacit component and thus cannot be completely transmitted not even by the person who possesses it.*" (p.320).

With a technology new to the company, the novel technology may be challenged by the "not invented here-syndrome"(Katz & Allen 1982), meaning a reluctance to apply or use the novel technology instead of what is already used as a solution - even though the novel technology may perform better or provide savings over the old technology.

The second aspect can be seen from a product-development point of view: the result of having developed a novel technology means the introduction of one or more novel sub-systems.

The term *technology integration* was investigated by Iansiti (Iansiti 1994; Iansiti 1995) and defined as:

> *"… the set of knowledge-building activities through which novel concepts are explored, evaluated, and refined to provide the foundation for product development."*
>
> (Iansiti 1994) p. 521-522

Changes in such a system are not limited to single elements, but a multitude of other design elements that together make up the system (Henderson 1990).

**How integration of technology contributes to this research**
In this work, integration of technology has been a part of the understanding of how this may affect existing products when new sub-systems based on novel technology are introduced. This is used in particular in Paper B.

### *3.4.4 PROTOTYPES*

Prototyping has been a part of the Engineering process for many years. By using prototypes, engineers are allowed to investigate different dimensions of a design to reduce the cost of costly iterations (Ulrich & Eppinger 2008).

Initiated from an understanding of models, Buur and Andreasen (Buur & Andreasen 1989) investigated the use of design models in engineering. Here the understanding of a model used to describe properties of an object was put forth, as illustrated in Figure 22.

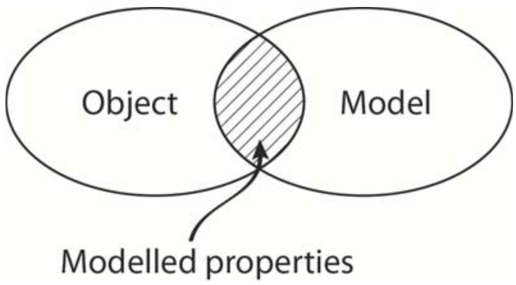


**Figure 22 - Models can be used to describe the properties of an object (redrawn from Buur & Andreasen 1989)**

> *"A design model is an artefact, which reproduces a subset of the properties of an object."*
>
> (Buur 1990) p. 34

They argued that the main difficulty is to choose a model type that models just the necessary number of product properties at the present stage of design. A vast amount of different models can be found within mechatronic development, however all are defined by two characteristics: the degree of abstraction (ranging from abstract to concrete) and the number of details (ranging from undetailed to detailed) (Buur & Andreasen 1989; Andreasen 1994). An overview of typical hardware models was given:

- Experimental set-up: verifying and evaluating function of principles or sub-systems.
- Design mock-up: specifying and evaluating appearance, ergonomics.
- Function model: verifying and evaluating the total product function.
- Prototype: evaluating usage, function, reliability, marketing properties.
- Pre-production series: evaluating manufacturing properties, product quality.

For these design models, the following purposes were stated as the basic operations of engineering design (Buur & Andreasen 1989):

- Define.
- Generate.
- Describe.
- Verify.
- Evaluate.
- Specify.
- Arrange.

Ulrich and Eppinger (Ulrich & Eppinger 2008) work with a similar understanding of design models; however, they seem to use prototype as a synonym. They define a prototype as:

> *"… an approximation of the product along one or more dimensions of interest."*
>
> (Ulrich & Eppinger 2008) p. 247

The definition is broad, but a classification of along two dimensions supports defining the type of prototype:

- Dimension 1: The degree to which a prototype is physical, as opposed to analytical.
- Dimension 2: The degree to which a prototype is comprehensive, as opposed to focused, i.e. how close to the actual product it is.

Prototypes can be used for the following four purposes (from (Ulrich & Eppinger 2008)):

- Learning.
- Communication.
- Integration.
- Milestones.

In addition, five principles can be used to guide decisions about prototypes (from (Ulrich & Eppinger 2008):

- Analytical prototypes are generally more flexible than physical prototypes.
- Physical prototypes are required to detect unanticipated phenomena.
- A prototype may reduce the risk of costly iterations.
- A prototype may expedite other development tasks.
- A prototype may restructure tasks dependencies.

**How prototyping contributes to this research**
Understanding prototypes has been a key point for a number of the papers in this research. Paper B and Paper E have benefitted from an understanding of prototypes in a technology development setting. In paper B the terminology and classification by Ulrich and Eppinger (Ulrich & Eppinger 2008) is used to define prototype.

## 3.5 Understanding Architectures and Platforms

Another central term in this thesis is the term *architecture*. An understanding of architecture is linked to the understanding of systems, as presented in Chapter 3.2.1.

### *3.5.1 Product Architectures*

For product architectures a number of definitions have been proposed. The following definitions are used to highlight different aspects of a product architecture, based on the perspective.

Ulrich (Ulrich 1995) defined it as "*(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components.*" (p.420). This definition has emphasis on the link between function and part.

Harlou (Harlou 2006) defined architecture as *"… a structural description of a product assortment, a product family or a product. The architecture is constituted by standard designs and/or design units. The architecture includes interfaces among units and interfaces with the surroundings"* (p. 83). In addition architecture was illustrated as a recursive phenomenon extending the vocabulary to product architecture, product family architecture, and assortment architecture. This definition highlights architecture as a recursive phenomenon.

Simpson (Simpson et al. 2001) defined platform as "… *the set of parameters (common parameters), features, and/or components that remain constant from product to product, within a given product family.*" (p.3).

From a different perspective, in relation to the life-phases a system goes through, the following definition was proposed:

> *"An architecture is a purposefully aligned structure of a system."*
>
> (Andreasen et al. 2004) p.2

This definition allows for an inclusion of purpose to be the difference between structure and architecture.

Architectures can be seen as integral or modular (Ulrich 1995) and modular architectures can be split into six categories (Jiao et al. 2007): component swapping, component sharing, fabricate-to-fit, bus, sectional, and mix modularity.

Modularity, based on architecture, allows designers to decouple specific functions and additionally allows for independent testing of sub-systems. Modules can be described as having the following characteristics:

- Modules are co-operative sub-systems that form a product, manufacturing system, business etc.
- Modules have their main functional interactions within rather than between modules.
- Modules have one or more well defined functions that can be tested in isolation from the system and are a composite of components of the module.
- Modules are independent and self-contained and may be combined and configured with similar units to achieve a different overall outcome.

after (Marshall et al. 1998), p. 1

From a documentation perspective, modularity can also reduce testing and certification of complex products (Jensen et al. 2015).

### *3.5.2 Production Architectures*

Similar to product architecture, production architecture has also been defined. Jepsen (2015) defined production architecture as:

> *"Fundamental concepts or properties of a production system embodied in its elements, relationships, and in the principles of the system's design and evolution that address the requirements and constraints from its intended applications."*
>
> (Jepsen 2015), p. 50

For a production architecture, a number of aspects can be considered:

- List of equipment: production lines, cells, machinery, tools and fixtures, mapped towards future launches (Mortensen et al. 2011).
- Variant creation points: Ramdas (Ramdas 2003) defined a *Point of Variegation*, where physical parts are dedicated to a product variant in the production, i.e. a decoupling point.
- Flexibility: determination of the range of product variants (Jain et al. 2013).
- Alignment: a dispositional relation leads to rule-based alignment (Andreasen et al. 2004).
- Commonality: there exist a common product structure and a common process structure within a product family (Schierholt 2001).

### *3.5.3 Knowledge Architectures*

In chapter 3.3.1 a close link between technology and knowledge was presented. Discussing knowledge architectures, Sanchez (2000) presents three forms of knowledge that can be used to codify organizational knowledge (see Table 4). The knowledge architectures can be used to identify knowledge assets in an organization and help to better target strategically useful organizational learning (Sanchez 2000).

**Table 4 - Three forms of knowledge (from Sanchez 2000)**

| Form of knowledge | Level of understanding | Capability derived from knowledge |
|---|---|---|
| Know-how | 'practical understanding' of how a current system works | Enables firm to maintain operations using current product and process architectures |
| Know-why | 'theoretical understanding' of why a system works | Enables making significant changes in current architectures and/or creation of new architectures |
| Know-what | 'strategic understanding' of purposes to which know-why and know-how may be applied | Enables firms to define feasible new product concepts based on kinds of product and process architectures |

**How architectures contribute to this research**

In this thesis, the majority of the academic output is based on the term of architecture. The three types of architecture, product, production, and knowledge all contribute to how architectures have been used in this research. The understanding of such a purposeful arrangement of a system has been the core of the approaches suggested in Papers B, D, E, and F.

### *3.5.4 Platforms*

Product platforms are utilized in a wide range of industries (Ben Mahmoud-Jouini & Lenfle 2010). Product platforms are mainly associated with reuse for a family of products. In a state-of-the-art review, Jiao et al. (2007) present a wide variety of definitions. However, a widely used definition is:

> *A platform is "… a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched"*
>
> (Meyer & Lehnerd 1997), p. 7

Such a platform is based on four common building blocks, consumer insights, product technologies, manufacturing technologies, and organizational capabilities. This is illustrated in the Power Tower (see Figure 23), which links product platforms to different market segments.

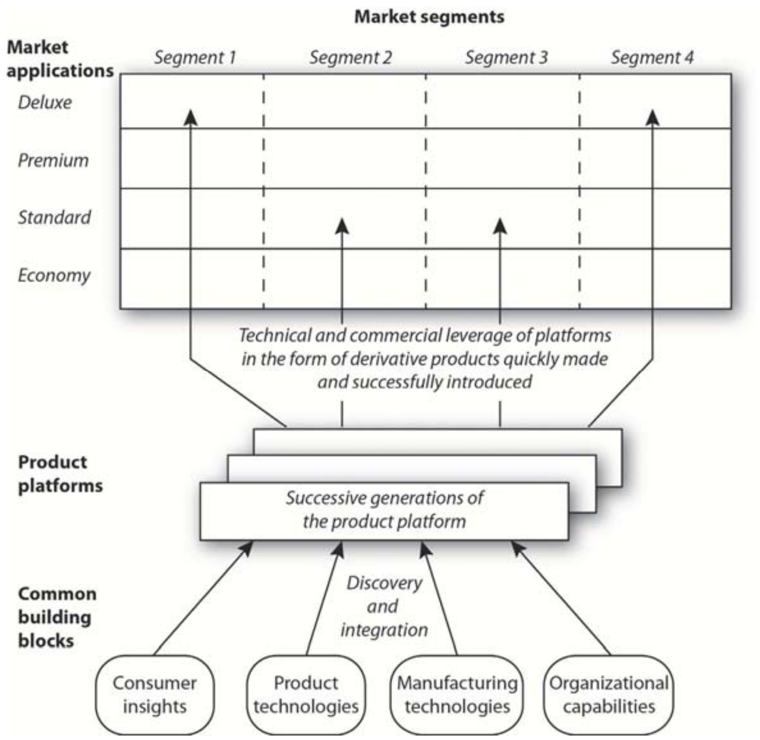


**Figure 23 - The Power Tower (adapted from Meyer & Lehnerd 1997)**

Halou (Harlou 2006) added to the understanding of platform with a more specific definition:

> *"A platform is a structural description of a product assortment, product family or a product. A platform is an instance of an architecture that only includes existing standard designs and their interfaces, .i.e. interfaces among the standard design, interfaces among standard designs and design unit and/or interfaces among standard designs and the surroundings."*
>
> (Harlou 2006), p. 86

Meyer and Lehnerd (1997) propose four strategic approaches to introduce platforms to the market:

- Niche specific platforms with little sharing of subsystems and manufacturing processes – where many product platforms exist, but with few shared sub-systems or
- Horizontal leverage of key platform sub-systems and manufacturing processes – where a product platform or one of the key elements within it is leveraged from one market niche to the next (within market application).
- Vertical scaling of key platform subsystems – where a range of different market applications within a segment are addressed with common product platform.
- The beachhead strategy: horizontal and vertical scaling – where the two former strategies are combined. Extensions are made to an initial platform to target different segments and applications.

The application of platforms has been repeatedly reported with good results and based on this Mahmoud-Jouini and Lenfle (Ben Mahmoud-Jouini & Lenfle 2010) argue that the question no longer is whether to invest in a platform or not, but how to design it.

Based on a review of different platform definitions, Kristjansson et al. (Kristjansson et al. 2004) suggested a more generally applicable definition of a platform as "… a collection of core assets that are reused to achieve a competitive advantage." (Kristjansson et al. 2004), p. 4, based on (McGrath 2000; Sawhney 1998; Robertson & Ulrich 1998).

**How product platforms contribute to this research**
The use of platforms is a widely accepted approach both in literature and industry. It has contributed to this research with the understanding of the common building blocks that make up a product platform. The understanding of platforms has been applied in paper E.

### *3.5.5 Technology Platforms*
Continuing from the product platforms, the recent development in literature has put a focus on technology platforms. A technology platform is often illustrated as underlying to a product platform, as illustrated in Figure 24.

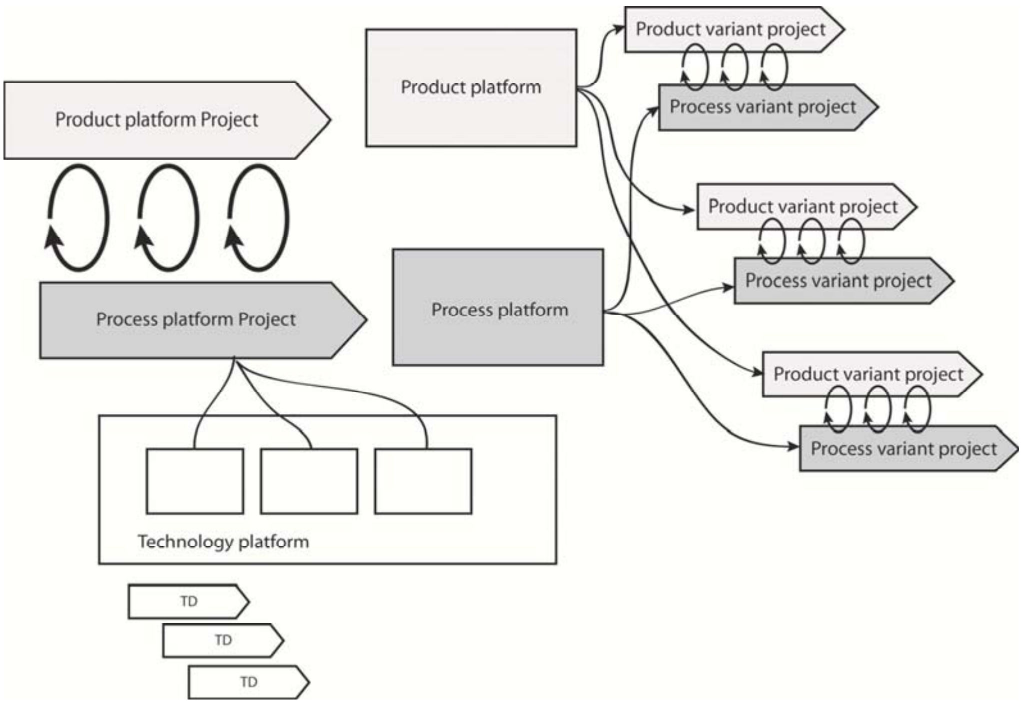


**Figure 24 - Technology platform and the relation to product platform (redrawn from (Bergsjo 2011))**

Technology platform projects can be defined as:

> *"… a set of initiatives organized around a macro-level functionality that helps to manage and optimize technology investments across multiple product platforms."*
> (McGrath 2000), p. 127-128

Levandowski et al. (Levandowski et al. 2012) find that technology platforms, compared to product platforms, can capture a larger range of elements, but do not lend themselves to the building block modules and interface structures of product platforms (McGrath 2000). A broader definition can be found that still focuses on reuse, but allows the broadest inclusion of knowledge:

> *"… matters of interest, which are important to reuse in technology as well as product and production system."*
>
> (Johannesson 2014), p. 127

Current approaches to describing a technology platform include the use of technology wiki, a central database supporting technology platform development and technology development in the form of better predictions to manage product and production development over time (Levandowski et al. 2012). Other contributions can be found in research after the millennium (Nasiriyar 2009; Nasiriyar 2010; Simpson et al. 2014; Wonglimpiyarat 2004; Kristjansson et al. 2004).

**How technology platforms contribute to this research**

The understanding of technology platforms allows for more abstract descriptions than product platforms, as well as a broader description. The technology platform is focusing on reuse of technology. The understanding of technology platforms has been applied in papers C and E.

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*"A lot of research is being done… …in the research, but I can guarantee that we are the first in the world who can mass produce the film. Mass production is the prerequisite of the technology becoming commercially attractive."* [translated from Danish]

- Michael Jørgen Hamann, 2012, CEO, Danfoss PolyPower (Andersen 2012), p. 5

# 4 PRACTICAL BASE

*In this Chapter, the DEAP technology and the industrial project that was studied is introduced. This is done to explain the context of the research as well as provide details on what the cases have been used for.*

*First the DEAP technology and its working principles are explained. Then, the background and timeline for the development of the DEAP technology under Danfoss auspice is presented. After that, the structure of the Innovation Fund Denmark project is explained. The project served as a technology test and evaluation project to mature the DEAP technology. Finally, the forming of the product and production, as well as the four different application cases designed in the research in the DEAP project are presented.*

The quote presented at the top of this page originates from the CEO of the company developing the DEAP technology which has been the practical base of this research. The quote was made in 2012 during the initial phase of the Innovation Fund Denmark DEAP project.

To start with, the next chapter will provide an explanation of what the di-electric electro active polymer (DEAP) technology is.

## 4.1 DEAP – THE TECHNOLOGY

Based on the patent granted in 2010, the core of the Danfoss PolyPower DEAP technology is found in:

> *"… a capacitive transducer comprising a set of electrodes arranged with a dielectric material there between, the electrodes and the dielectric material thereby forming a capacitor, wherein the capacitor is arranged in such a manner that electrical energy supplied to the electrodes can be at least partly converted directly into mechanical work for actuation by the transducer."*
>
> (Clausen & Benslimane 2010), p.29

The PolyPower DEAP technology itself is based on Maxwell's pressure, where two corrugated films, each consisting of an electrode on a soft, but non-compressible dielectric material, are sandwiched together to form an elastic capacitor. A single metalized layer is referred to as DEAP *film* and the combination of two metalized layers makes a DEAP *laminate*, as illustrated in Figure 25. As an electrical field is applied (the electrical energy), the two layers are pulled towards each other, creating an elongation of the film (the mechanical work). Danfoss PolyPower patented the use of corrugated surfaces, allowing solid metals to be used as highly conductive bendable (effectively "stretchable") electrodes.

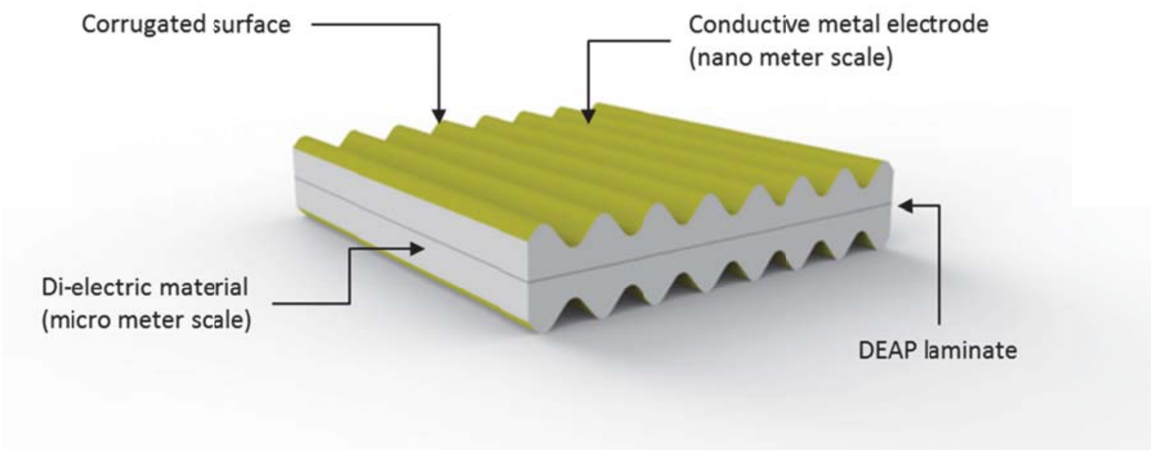


**Figure 25 - The elements of a DEAP laminate**

The elongation is described by the following equation:

$$P = \varepsilon_0 \varepsilon_r (E^2) \quad (1)$$

where

$P$ = the Maxwell's pressure

$\varepsilon_0$ = the permittivity in vacuum

$\varepsilon_r$ = relative permittivity, dielectric material

$E$ = the electric field across electrodes

[from (Tryson et al. 2009), p.6]

As the film is corrugated, the elongation is along the compliant direction (see Figure 26).

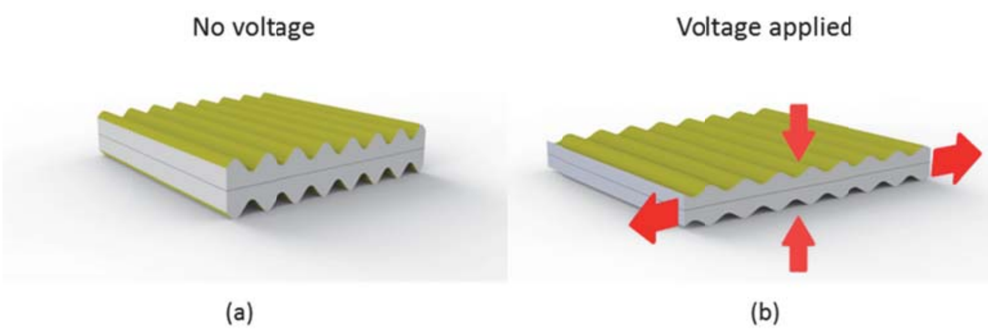


**Figure 26 - DEAP laminate (a) with no electrical field applied, (b) with electrical field applied, becoming longer and thinner**

Although having a corrugated surface, the corrugation is not visible to the naked eye, as the thickness of the film is ~50µm. Therefore, when inspecting a piece of DEAP film, the corrugation makes the surface reflect light as illustrated in Figure 27a.

Film breakdowns can also occur (see Figure 27b). These occur when too high a voltage is applied, or due to ageing, and results in decrease in performance or rendering the transducer inoperable.

**Figure 27 - DEAP-film (a) a piece of DEAP film (b) a piece of DEAP film with breakdowns [right photo: Emmanouil Dimopoulos]**

In the DEAP project the dielectric material was developed in WP 1. A number of material updates were developed over the project period, each increasing different material parameters by synthesizing different material compositions. The DEAP technology used by Danfoss PolyPower was used to produce a DEAP corrugated film for three main transducer types, as illustrated in Table 5.

**Table 5 - The three types of application of the DEAP technology**

| Application | Description | DEAP project |
|---|---|---|
| Actuator | When applying an electric field across a capacitor, electrostatic forces will try to force the plates of the capacitor towards each other. | Yes |
| Generator | The amount of stored energy changes when the capacitance of a DEAP element is changed. This is a result of mechanical force on the element. | Yes |
| Sensor | External mechanical force deforms the PolyPower film and results in a capacitance change. | No |

In the DEAP project, the focus was on the use as actuator and generator. The comparison of the DEAP technology to other technologies is depicted in Figure 28, showing how the technology is positioned in mid-range Strain and Force density.

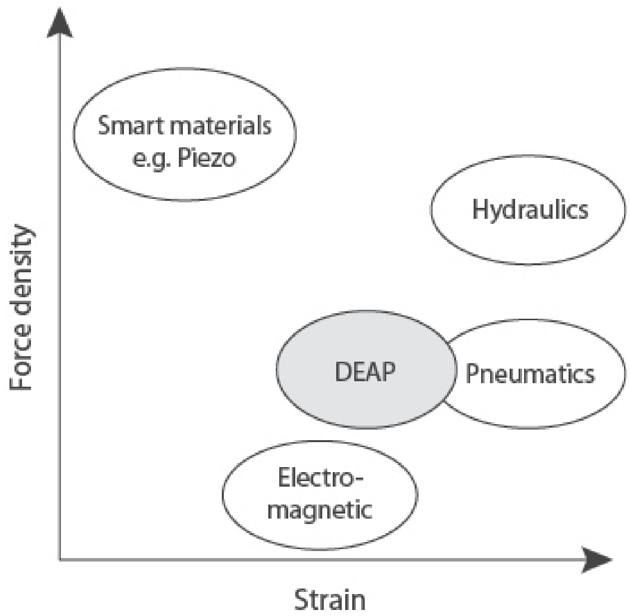


**Figure 28 - DEAP compared to other technologies [redrawn from DEAP project material]**

The development in the DEAP project entailed multiple intertwined areas in which separate parts of the technology were developed. The value chain, from the base polymer material to application, potential products, was covered (Tryson & Kiil 2010).

In the DEAP project it was expected that the DEAP dielectric material could be developed to provide an increase in performance as well as a decrease in size.

## 4.2 BACKGROUND

The DEAP technology was initially investigated by Danfoss in 1995 as it was assessed to be an innovative technology with a huge potential for future actuators. This early investigation ran as a side-project in the Danfoss organization and the development of the technology was "under the radar" until 2006, where a formal project team was formed, with the aim to develop a scalable concept for DEAP actuators. By 2008, the project had delivered a basic concept for production of large scale DEAP film and illustrated how this could be used to produce larger actuators. In addition, the core concept had been patented. Based on this, the company Danfoss PolyPower (2008-2014) (Polypower n.d.) was founded with the aim to commercialize the technology.

### *4.2.1 VALUE CHAIN POSITION*

The performance of the DEAP actuator depends heavily on the dielectric materials used, the process with which the thin films are made, as well as the construction of actuators from this thin film. Having IPR on the key concept of corrugated film, DPP sought to create the full value chain development of the technology. This was necessary as the performance of the actuator originates from combined progress within the fields of material, film and actuator design, although the main scope of interest for the company was in the development and manufacturing of DEAP elements (transducers) and devices delivered to e.g. OEM customers (see Figure 29).

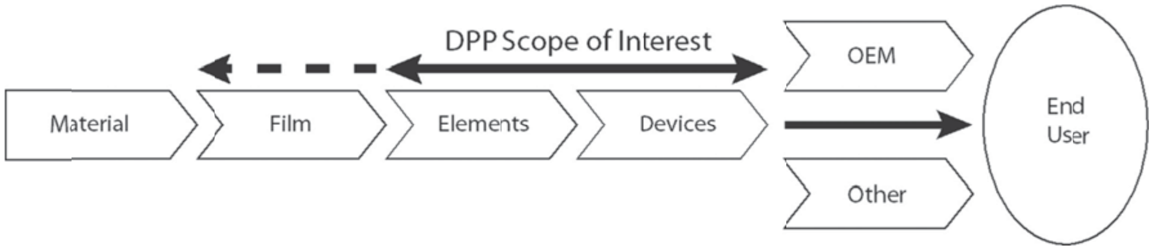


**Figure 29 - Value chain position for DPP**

### *4.2.2 DANFOSS DEAP DEVELOPMENT STAGES*

Figure 30 shows the different development stages seen from a Danfoss perspective. By the end of 2014 Danfoss PolyPower A/S had decided to reduce the activities gradually with the eventual ending of the DEAP project. However, the DEAP research project was carried out until its planned end in April 2015. EAP research continued after this in both industry and academia.

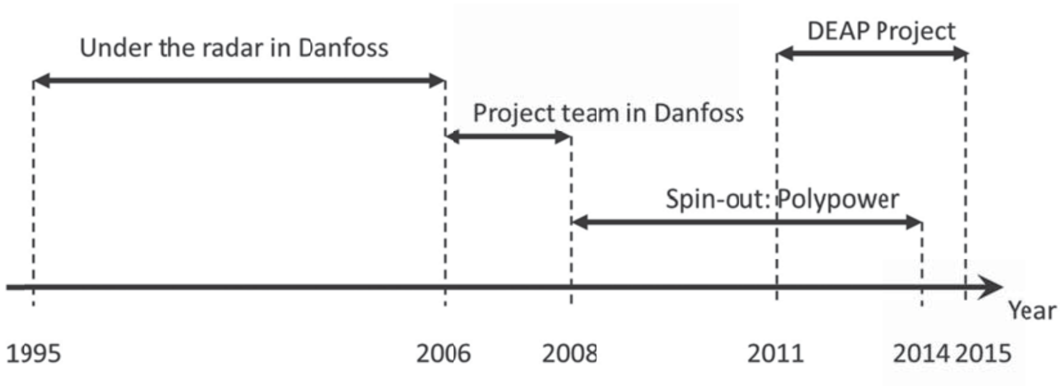


**Figure 30 - Timeline of the DEAP venture**

## 4.3 THE DEAP PROJECT

The main project studied in this research had the title "Highly efficient low cost energy generation and actuation using disruptive DEAP technology", and was classified as a larger, technology-driven public-private partnership project (Hansen 2013). The project had a duration of four years and during the project more than 120 people were involved.

### *4.3.1 THE DEAP RESEARCH PROJECT*

In 2011, a DKK 49 million (~ EUR 6,6 million) grant was given by Innovation Fund Denmark (IFD), formerly the Danish National Advanced Technology Foundation (DNATF) to a consortium of five institutes from three universities and seven Danish companies for a four-year research project (2011-2015) on DEAP technology (Mogensen n.d.). The budget of the project amassed to approximately DKK 95 million (~ EUR 13 million). The DEAP research project has been the main focal point of this research and was followed over the period from July 2012 to the end in April 2015. The participating partners can be seen in Table 6.

**Table 6 - Overview of the partners in the project**

| Academic Partners | Industrial Partners |
| --- | --- |
| • *Technical University of Denmark* (departments: Mechanical, Chemical, and Electrical Engineering departments)<br>• *Aalborg University* (Energy department)<br>• *University of Southern Denmark* (Software) | • *Danfoss PolyPower*<br>• *Danfoss*<br>• *WaveStar*<br>• *Bang & Olufsen*<br>• *Polyteknik*<br>• *ESS Technology*<br>• *Noliac* |

The partners were distributed over most of Denmark, and were organized in a virtual company setup (see Figure 31).

Despite the diverse locations of the project partners, an effort was made to have frequent meetings. The possibility of incorporating a virtual meeting space with telecom and screen sharing was used to reduce traveling time and costs.

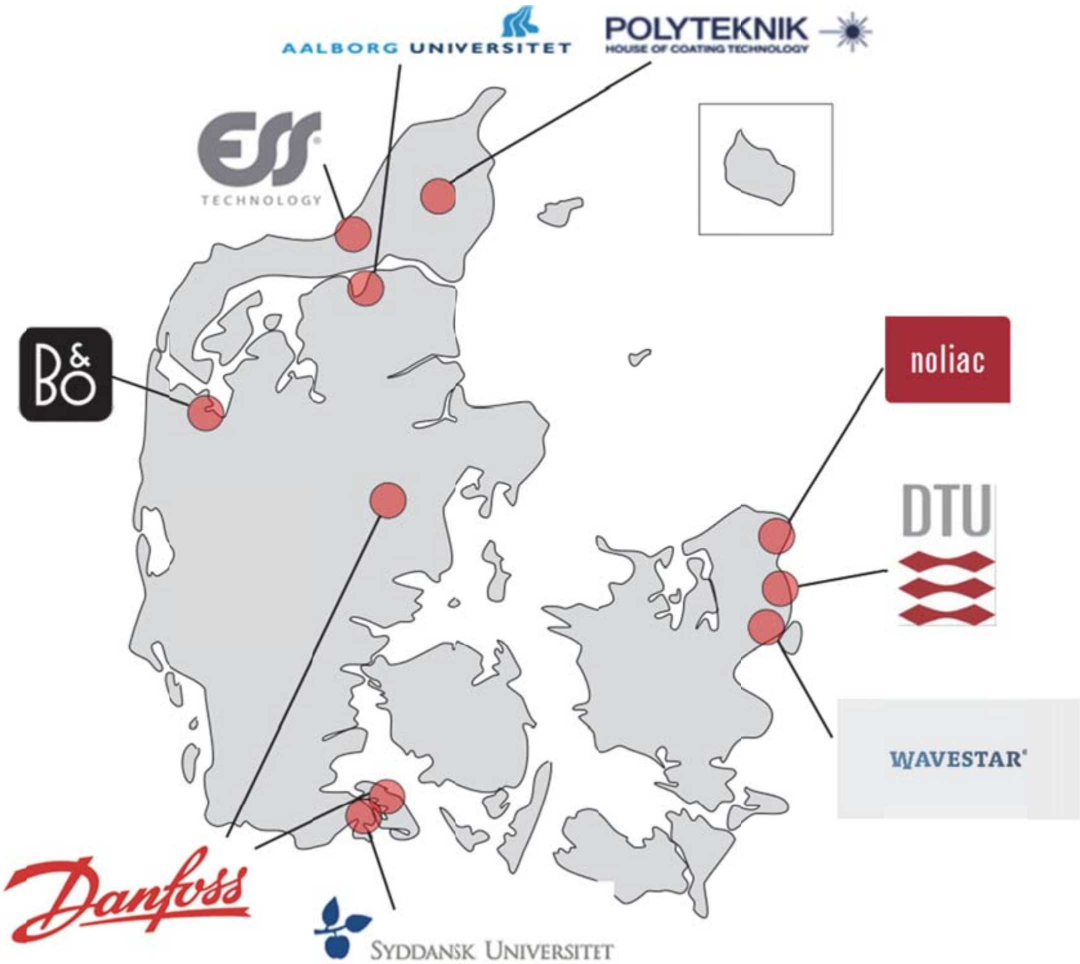


**Figure 31 - Geographical overview of Denmark and the locations of the project partners**

### 4.3.2 *PROJECT SETUP*

The project was divided into 10 Work Packages (WPs) to allow specific development topics to be pursued, as seen in Figure 32. The topic of WP 0 was Project management. WP 1-5 were focused on the technology platform, i.e. the development of core material (WP 1), DEAP thin film production (WP 2), transducer element platform (WP 3), high voltage power electronics (WP 4), and engineering tool development (WP 5). WP 6-9 focused on applying DEAP actuators within different application systems, i.e. in an incremental motor (WP 6), an energy harvesting device (WP 7), a heating control valve (WP 8), and a loudspeaker (WP 9). Each of these WP's had its separate WP leader. The project manager of WP 0 was responsible for the overall project, coordination and integration, and the WP leaders of WP 1-9 were responsible for the technical day to day coordination in each WP.

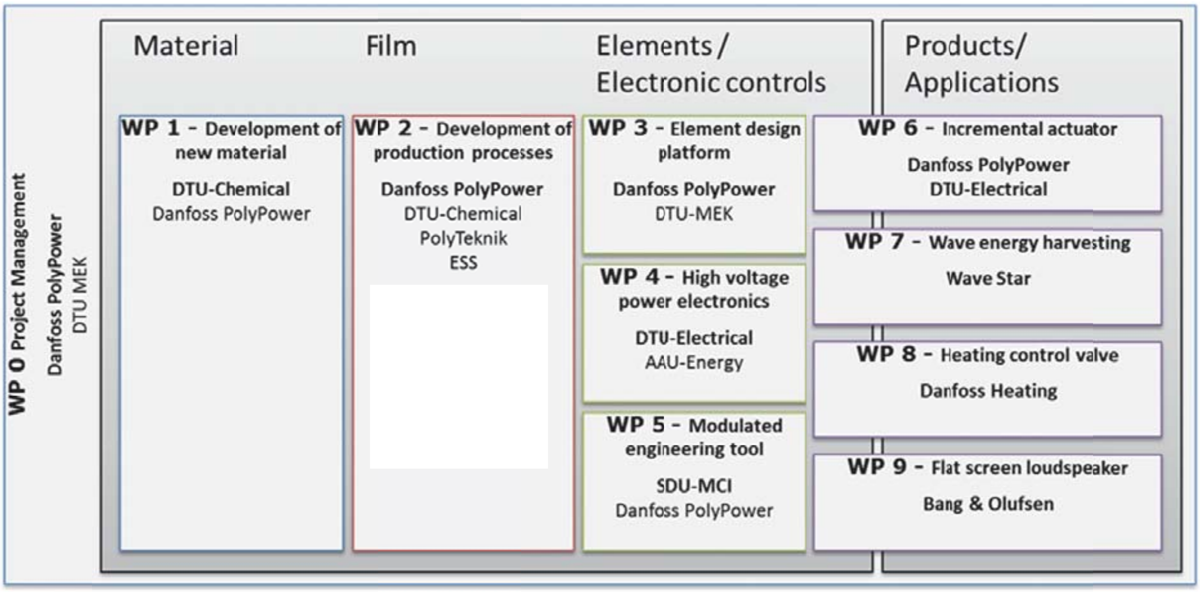


**Figure 32 - An overview of the Work Package division in the DEAP project [Adapted from DEAP project material]**

The objectives of the DEAP project were, among others:

- To mature the DEAP technology to reach a quantum leap in performance.
  - Find improved material (WP 1).
  - Optimize production processes (WP 2).
  - Develop platform based DEAP elements (WP 3).
  - Invent an engineering tool for design actuators and generators (WP 5).
- To develop high voltage electronic controls (WP 4).
  - With low power, high voltage actuator control (energy recovery, IC).
  - With efficient energy harvesting control.
- To demonstrate DEAP solutions in four key applications.
  - As incremental motors (WP 6).
  - In wave energy systems (WP 7).
  - As compact in-line heating valves (WP 8).
  - As loudspeakers (WP 9).
- Create maximum innovation and business value from project.

[from DEAP project material]

### 4.3.3 Research Focus

The author was part of the project management work package (WP 0) and therefore had contact with most of the work packages. The author also had a sparring with the dedicated researcher linked to WP 3 as both were part of the Section for Engineering Design and Product Development at DTU Mechanical Engineering.

The DEAP project covered a full value chain development to a novel technology with a potentially large application scope. This meant also a very complex development environment with the need for steering the development in the "most valuable" direction on a high level, while aligning the activities within each of the technical fields.

The main focus of this research was centered on the leadership with regard to aligning the technology development with the exploration within the application work packages (WP 6-9). This included amongst other things the work that created the foundation for the publication of Paper A and Paper B. Interaction with high voltage power electronics development and the modulated engineering tool (WP 4-5) happened through the work in the application work packages.

A secondary focus was to provide support to the definition of a conceptual product platform in WP 3 and drive the definition of a production architecture representation in WP 2. Based on this, Paper D, Paper E, and Paper F were published.

The knowledge gained throughout the project, i.e. meetings and experience with all of the work packages was put to use for development of the framework presented in Paper C, to enable a prioritization approach, based on multi-architecture coherence.

## 4.4 Forming Product and Production

One of the main tasks of the DEAP project was to develop a DEAP transducer platform (WP 3) as well as ramp up the production of the basic DEAP thin film (WP 2). As indicated in Table 2 in Chapter 2.5.1, the involvement of the researcher was lower in these two work packages than the involvement in the application work packages (WP 6-9).

### 4.4.1 A Platform Approach to the Development (WP 3)

No "killer" application had been identified prior to the DEAP project. Therefore it was uncertain what applications would prove most promising for commercializing the technology. A platform approach was adopted and a generic product architecture was defined to support the overview of the building blocks making up a DEAP transducer. Based on this architecture, the different technologies making up a DEAP transducer could be identified and developed.

Although more than a handful of transducer concepts were defined, only two were realized for use in the applications: Axial 1 and Linear. Axial 1 was used in WP 6, WP 8, and WP 9, while Linear was used in WP 7 (see Figure 33).

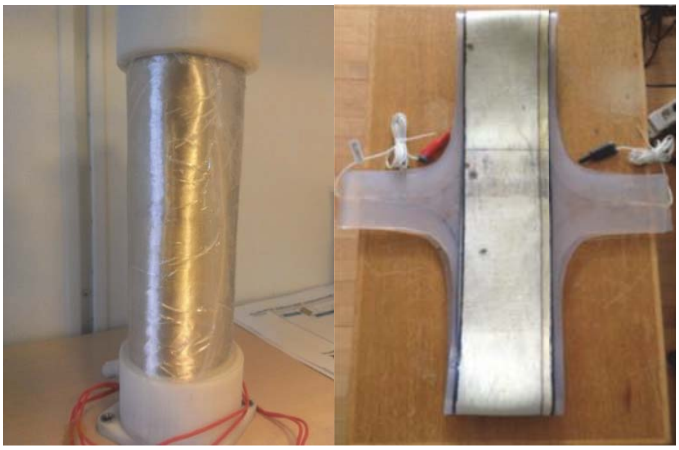

**Figure 33 - The two dominant DEAP transducer designs in the DEAP project Axial 1, actuator (left), Linear, generator (right) [right photo: Emmanouil Dimopoulos]**

The transducers defined in WP 3 were designed in close dialogue with the application projects to fit in the best possible way. Some of the challenges encountered in the four application projects demanded a revisit of some of the technologies making up a transducer, e.g. the electrical connection.

**The contribution from this research:** The work in WP 3 was supported with the Conceptual Product Platform (CPP) presented in Paper E.

### *4.4.2 Ramp-up of DEAP Film Production (WP 2)*

The main objective of the production work package was to ramp up the production of the DEAP film from laboratory production to a production setup capable of continuous, industrial production. During the DEAP project, major improvements were made to increase the production process capacity, as well as improve the process quality. The work done in this work package was highly dependent on the material development (WP 1) to enable the aimed performance increase.

A number of process steps, see for instance Figure 34, were used to create a DEAP film and many of these affected the characteristics of the film (see Chapter 3.2.1 for *characteristics*). Both defining processes and variation had a potentially high impact on (a) the investments, (b) the capacity, and (c) the types of film that could be produced.

**Figure 34 - One of the improved processes in the DEAP film production [Photo: Tómas V. Guðlaugsson]**

The work in the production work package was supported with the production architecture work presented in Paper D and Paper F.

## 4.5 Four Application Projects

Four applications of the DEAP technology were tested in the DEAP project as illustrated in Figure 32. These four are presented in this chapter.

For each application three iterations were originally planned. The development of the first demonstrator iterations laid the basis for developing the TePPAT modeling tool presented in Paper B.

**The contribution from this research:** The work in the four application projects was supported with the TePPAT modeling approach presented in Paper B. The TePPAT was used to model the demonstrator instances by capturing information on the *purpose*, the *concept,* and the *architecture*. The TePPAT was used as a tool for the development teams to communicate the status of the development in and out of meetings (see Figure 35).


**Figure 35 - Use of the TePPAT during development meeting**

The TePPAT was used, for e.g.:

- Discussing the design of the demonstrators.
- Planning ahead (back casting and future versions).
- For the individual prototypes.
    - Capturing and managing success criteria.
    - Capturing and explaining the concept.
    - Capturing and managing architecture instance.
- Providing control of success criteria for integration test and reporting.

### 4.5.1 INCREMENTAL MOTOR (WP 6)

The incremental motor originally appeared as a concept in the conceptual work of transducer types in the transducer work-package (WP 3). In this principle more actuators are combined in a device and activated in combination to create an incremental motion.

***Origin:*** An incremental motor can be classified as either an (a) walker or (b) pusher. A walker walks on or along a defined path while a pusher is stationary and pushes an object from A towards B. In the DEAP project, the walker concept was pursued.

***Goals:*** An initial work was put into investigating the potential benefits of using DEAP actuators over piezo and pneumatic concepts. Three capabilities were found suitable for pursuing further: simple design, flexible structure, autonomous.

The main goals for the work package were to illustrate these capabilities. First, basic walker functionality on a straight path should be demonstrated. Then, operation on a curved path was planned to demonstrate flexible structure, as well as simplifying the design. Finally, operation on curves of different sizes should conclude the demonstrator development.

***Demonstrators:*** Two demonstrators were built for the goals of basic walker functionality and curved path operation (see Figure 36). Additionally, bi-directional motion was demonstrated. Due to time-constraints, the third demonstrator was cancelled. The demonstrators built in this work package used the Axial 1 actuator, however in different sizes.

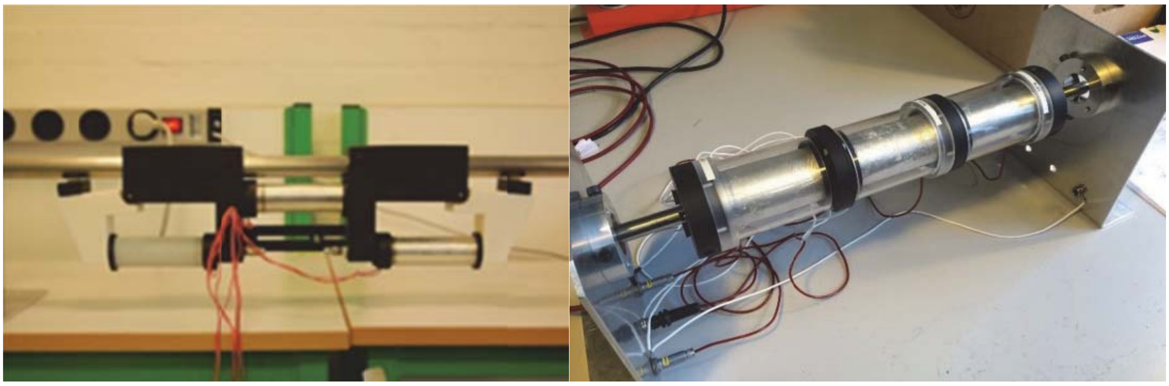

**Figure 36 - The two demonstrators in WP 6 (left) demonstrator 1 – walker on a straight path (right) demonstrator 2 – walker on a curved path [Photos: Danfoss Polypower]**

### 4.5.2 WAVE ENERGY HARVESTING (WP 7)

In this application the DEAP transducer was used as an energy generator (WP 7) by converting mechanical energy into electrical energy in the context of wave energy conversion. In this work package the DEAP generator was investigated as a replacement to the existing hydraulic sub-system in the WaveStar installation.

***Origin:*** The work package was made together with WaveStar A/S, a company working to change the world's mindset about how to produce clean energy (WaveStar n.d.). The company does this by harvesting mechanical energy from waves and converting this into electrical energy sold to the electrical grid. During the DEAP project, the largest WaveStar installation was a half-scale, 600kW machine (see Figure 37).

**Figure 37 - WaveStar demonstration installation at Hanstholm, Denmark [Photo: WaveStar]**

***Goals:*** Initially, the final goal of the work package was to construct a 1kW wave energy harvester. This goal was broken down into a milestone deliverable for each demonstrator to take into account the concurrent development of the DEAP material, unlocking increased performance. The planned demonstrator steps were: 10W, 100W, and 1kW. The vision was targeted to 50kW. In addition to a specific power output a main requirement was to demonstrate high energy conversion efficiency.

***Demonstrators:*** Three iterations of demonstrators were made, however on the same test setup in a rotary motion running 0,5-2Hz, as illustrated in Figure 38. Up to four DEAP generator elements could be mounted in the demonstrator at the same time with three point stroke positions each (40, 60, 80%).

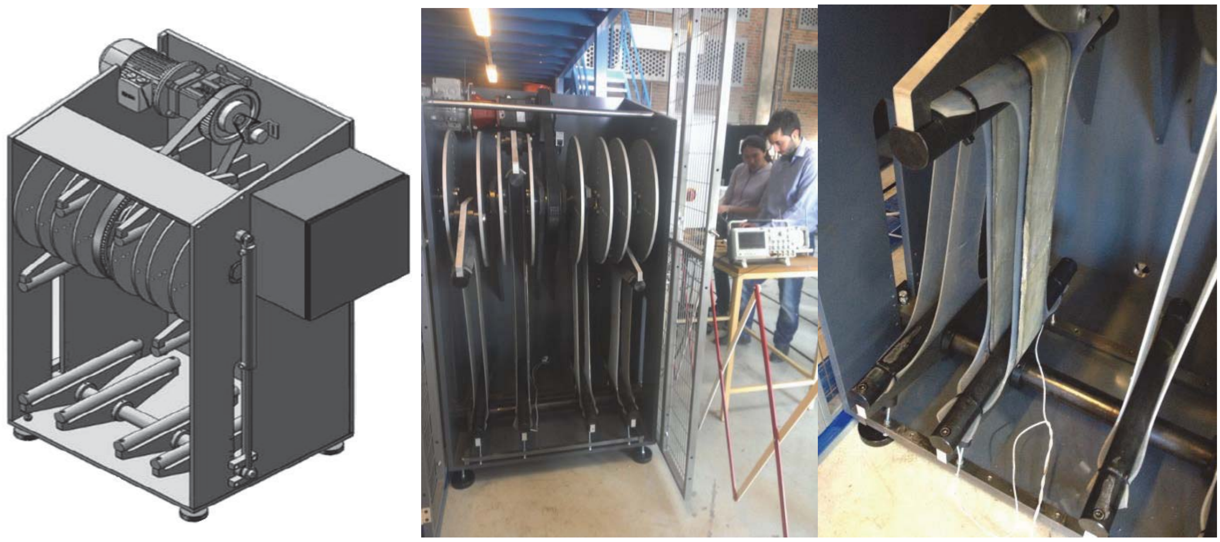

**Figure 38 - (left) CAD drawings of demonstrator, (middle) picture of the built demonstrator used as demonstrator 1, 2, and 3, and (right) the DEAP Linear transducers attached to the machine [left figure: CAD from project material, right photo: Emmanouil Dimopoulos]**

The main difference between the demonstrators was the DEAP generator elements, however with improved design. One of the major challenges in the work package was the quality of the DEAP generator elements as multiple generator elements failed electromechanically, i.e. rendered electrically inoperable and without ability to hold a capacitive charge.

The work package was concluded by stating that the use of DEAP generator elements used as a generator is not proven and fundamental research still needs to be done.

### *4.5.3 Heating Control Valve (WP 8)*

In the heating application exploration the DEAP actuators were used to pursue novel concepts for replacing the step-motor found in electronic thermostats. Utilizing the DEAP technology was envisioned to provide a potential in reducing the size of the thermostat or providing a complete in-line actuation and/or improving power efficiency, hence increasing battery lifetime.

***Origin:*** The work package was made together with Danfoss Heating Systems (DHS), a world-wide company producing valves, thermostats among others (see Figure 39).

**Figure 39 - A 014G0001 thermostat, part of the "living by Danfoss" series [from (Danfoss 2015)]**

The Danfoss thermostats range from simple, manual thermostats to autonomous, system-connected thermostats.

***Goals:*** The goals of the heating valve application were to investigate the use of the DEAP actuator in different concepts competing with existing solutions on parameters such as efficiency, cost, or compactness.

The purpose of the first demonstrator was to implement a DEAP actuator and driver electronics as a stand-alone, add-on system powered by batteries to demonstrate basic open/close functionality. The decision of the following demonstrators' design was initially left open while a vision for a Danfoss DEAP product system was defined.

***Demonstrators:*** Two iterations of physical demonstrators were completed, as illustrated in Figure 40. Both demonstrators used an Axial 1 actuator. A third iteration was made as a gap analysis (reached performance compared to desired performance).

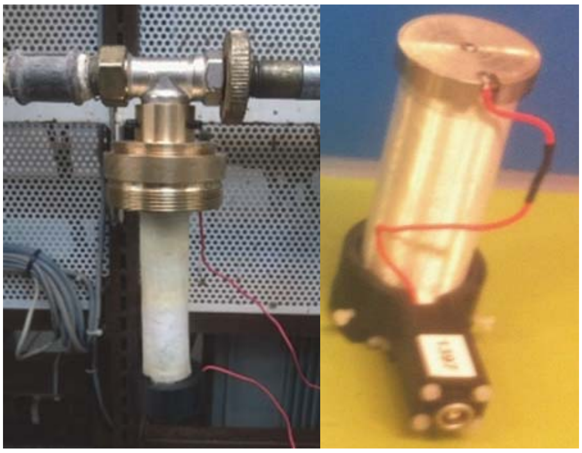

**Figure 40 - The two demonstrators in WP8 (left) demonstrator 1 (right) demonstrator 2 [Photos: Danfoss PolyPower]**

The first demonstrator was built with the focus on open/close functionality. In addition, power efficiency and feasibility of 10 year battery time was explored.

The second demonstrator further investigated the battery lifetime in addition to reducing size, pulse mode actuation, and higher energy efficiency. A working system was made and tested with continued operation after 5000 cycles.

The third development iteration was used to analyse the gap between the reached performance and the requirements for an envisioned Danfoss DEAP system.

In the work package the GAP analysis provided the conclusions that significant material improvements of the DEAP dielectric material were needed, but also that the DEAP actuator showed promising results with pulse-mode actuation.

### 4.5.4 LOUDSPEAKER (WP 9)

In the final work package the DEAP actuators were used to test reproduction of audio signals, i.e. as a loudspeaker. The application was used to test the DEAP transducer in the frequency range of a mid-range loudspeaker, approximately 100Hz -3500Hz.

***Origin:*** The work package was made together with B&O, a company known for its audio and video products. For making the DEAP technology potential interesting as a loudspeaker, it should create new opportunities or compromises compared to regular loudspeaker transducers used by B&O. This could for instance be related to size, cost, quality, or geometry.

***Goals:*** The overall goal for the work package was to reproduce audio signals with the use of one or more DEAP transducers. Additionally, the goals were to investigate the above potential for using the DEAP technology.

First a basic concept was to be built with the purpose of investigating how the DEAP material behaved when used to generate sound and learning about possible challenges for future demonstrators. The following demonstrators were based on the learning obtained in demonstrator 1 and aimed at e.g. increasing sound pressure and improving frequency response.

***Demonstrators:*** Three development iterations were completed: two with physical demonstrators and one with the development of a simulation model that was used to predict the behaviour and potential of a DEAP transducer as a loudspeaker.

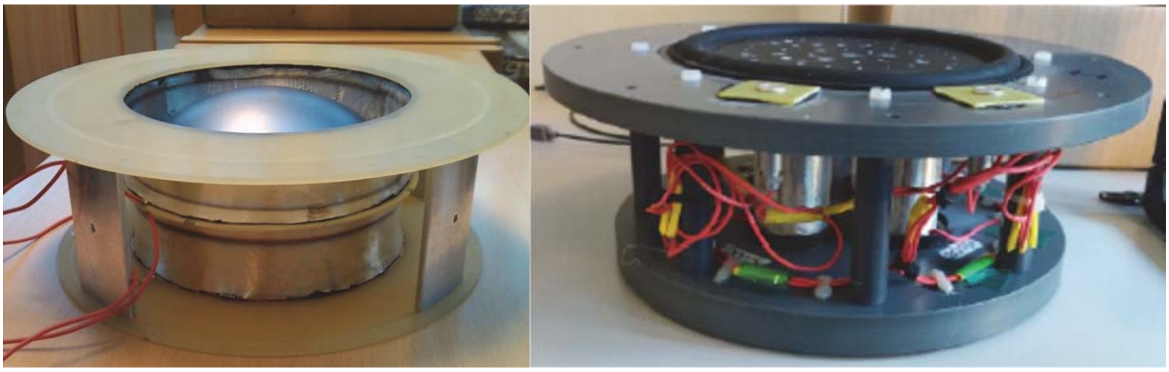

**Figure 41 - The two demonstrators in WP 9 (left) demonstrator 1, a push-pull concept (right) demonstrator 2 – a flat diaphragm concept [Photos: B&O]**

The two physical demonstrators in WP 9 both used the Axial 1 actuator (see Figure 41). Demonstrator 1 was a push-pull concept, where two stacked DEAP held a diaphragm in between them and were driven in antiphase. The actuators replaced the magnetic voice coil found in a regular loudspeaker.

In demonstrator 2, four DEAP actuators in phase were used to drive a flat diaphragm.

In the third demonstrator iteration, focus was shifted towards verification of a simulation model (lumped parameter model) to enable simple prediction of transducer designs based on DEAP transducers.

The work package was concluded with the application outlook of the DEAP technology in (a) a lower frequency bandwidth, or (b) actively using resonances.

## 4.6 Concluding the Practical Base

The DEAP project, as presented in the previous chapters, was a project with many challenges from its outset. This is indicated by the fact that:

- A new technology was to be matured.
- The whole value chain was under development in parallel.
- A wide range of application areas was possible for the technology.
- The application areas set completely different requirements for the technology.

In the DEAP project, the challenges were met in a project structure with nine work packages focusing on:

- Improving the performance parameters of the dielectric material.
- Setting up and controlling the production of the DEAP film. Corrugations were to be made in µm scale and electrode in nm scale.
- Defining the transducers making up the product portfolio.
- Designing and building high-efficient electronic drivers operating in the range 0-2500V.

- Developing and validating a model to correctly simulate transducer behaviour.
- Designing, building, and testing three iterations of technology demonstrators in four vastly different application projects with each their key parameters.
- Coordinating the integration of activities in all the different, but interlinked development teams.

Each of these development areas were a big task in themselves, and could easily accumulate 20 years of development if pursued with a serial development strategy. This was one of the reasons for choosing the parallel development strategy in the DEAP project.

Having all areas under development concurrently presented a chance of rapid progression in multiple areas; however, it also introduced high complexity due to interdependencies between the areas and increased the risk of e.g. delays if milestones and deliverables were not met. Therefore, the DEAP project had a high need for coherent architecture work to support the development.

In conclusion, the DEAP project was an example of the fine art of developing everything - at the same time.

*"Data! Data! Data!" he cried impatiently. "I can't make bricks without clay."*
- Sherlock Holmes, The Adventure of the Copper Beeches

# 5 RESULTS

*This chapter presents the results of this research in the form of summaries of the papers appended to this thesis.*

*The summaries contain descriptions relating to the research questions, research contribution, research method, and reflection on the results.*

The purpose of this chapter is to present the results from the PhD, extracted from submitted journal and conference papers. The strategy for communicating the research included submitting papers for engineering conferences related to the Design Society (Paper A, Paper D) as well as submitting papers for ISI-indexed journals.

## 5.1 PUBLICATIONS WITHIN THIS RESEARCH

*Paper A – **Ravn, P.M.**, Guðlaugsson, T.V., Mortensen, N.H., "Tasks and challenges in prototype development with novel technology – an empirical study", Conference proceedings of ICED 2015, Milan, Italy.*

*Paper B - **Ravn, P.M.**, Guðlaugsson, T.V., Mortensen, N.H., "A multi-layered approach to product architecture modeling – Applied to technology prototypes", Journal of Concurrent Engineering: Research and Applications.*

*Paper C - **Ravn, P.M.**, Mortensen, N.H., Hvam, L., "Identification of critical technology building blocks".*

*Paper D - **Ravn, P.M.**, Guðlaugsson, T.V., Mortensen, N.H., "Visual Modelling of Pilot Production to Support Decision Making in Production Development", Conference proceedings of DESIGN 2014, Dubrovnik, Croatia.*

*Paper E - Guðlaugsson, T.V., **Ravn, P.M.**, Mortensen, N.H., "Front End Conceptual Platform Modeling", Journal of Concurrent Engineering: Research and Applications.*

Paper F - *Guðlaugsson, T.V., **Ravn, P.M.**, Mortensen, N.H., "Modelling production architectures in the early phases of product development", Concurrent Engineering: Research and Applications.*

Please revisit Figure 8 and Table 2 to see the relations between publications and the research stages as well as research questions.

The papers are presented in an order fitting the three main areas. Thus, the presentation order is:

- ***Paper A*** and ***Paper B*** (Product architecture instances for prototypes testing novel technology)
- ***Paper E***, ***Paper D***, and ***Paper F*** (Product architecture and production architecture in early development setting)
- ***Paper C*** (Architecture coherence as a basis for prioritization)

## 5.2 Product Architecture Instances for Prototypes Testing Novel Technology

The papers associated with integrating a novel technology into prototypes are Paper A and Paper B.

### 5.2.1 *Paper A*

**Title:** "*Tasks and challenges in prototype development with novel technology – an empirical study*" (Ravn, P. M., Guðlaugsson, T. V., Mortensen, N. H.)

**Conference:** ICED 2015 – 20th International Conference on Engineering Design

**Contribution:** First author

**Cases:** Case 1, Case 4-7

**Research Questions answered:** The research question specifically answered is 1a:

☑ RQ1a: What are the tasks and challenges of developing prototypes with input of a novel technology?

**Contribution to the research:** The contribution from the paper is a thematic analysis of the tasks and challenges from the development of technology prototypes. The analysis contributes to answering the first research question as part of the research clarification.

**Research method:** The research method for this paper was a two-prong attack as illustrated in Figure 42. From theory, mainly papers and books, tasks and challenges were identified.


**Figure 42 - Method approach from theory and from industry [from (Ravn, Guðlaugsson, et al. 2015b)]**

From industry, 138 monthly reports from a three-year project were used as a base for a thematic analysis of progression (tasks) and challenges. Tasks and challenges were each mandatory sections of the monthly reports. In total, 540 task entries and 226 challenge entries were identified and analysed in two coding cycles. A data handling report was used to document all steps and team coding was used to strengthen the reliability of the coding (Miles et al. 2014).

**Results:** 17 task themes and 9 challenge themes were identified for all four projects in total as illustrated by Table 7 and Table 8.

**Table 7 - Task themes, percentage, and theme descriptions for tasks [from (Ravn, Guðlaugsson, et al. 2015b)]**

| Themes (Abbreviation) | % | Theme description |
|---|---|---|
| Test (TEST) | 14,1 | Test of systems or sub-systems developed within the projects. |
| Detailed design (DET-DES) | 13,5 | Detailed design activities. |
| Implementation (IMPL) | 13,0 | Constructing and installing the system or sub-systems |
| Project Management (PROJ-MAN) | 11,4 | Project definition, scoping, agreements, planning, and resource allocation activities, |
| Analysis (ANA) | 8,3 | Simulations, calculations and other tasks involving an analysis of system or sub-system performance |
| Conceptual design (CON-DES) | 8,2 | Concept design, brainstorms. |
| Problem (PROB) | 7,5 | Problems, failures, and repair activities |
| Documentation (DOC) | 5,7 | Documentation of system, test, or project progress. |
| Academic work (ACA-WOR) | 4,0 | Entries directly related to academic work, such as publishing and conferences, as well as preparations for these. |
| Specification (SPEC) | 3,1 | Specification of systems or sub-systems, current or future |
| Collaboration (COL) | 2,9 | Entries explicitly communicating sharing of knowledge and / or resources across project organisations |
| Procurement (PROC) | 2,3 | Finding, ordering, and purchasing parts or components from third parties. |
| Delay (DEL) | 2,2 | Delays in project due to various causes. |
| Review (REV) | 2,0 | Review of system or development activities. |
| Embodiment design (EMB-DES) | 0,9 | Embodiment design activities. |
| Limited Resources (LIM-RES) | 0,7 | Explicit entries on limited resources or limited progress due to limited resources |
| Familiarization (FAM) | 0,1 | Explicit familiarisation of project members with the technology and / or project. |

**Table 8 - Challenge themes, percentage, and theme description [from (Ravn, Guðlaugsson, et al. 2015b)]**

| Code (abbreviation) | % | Code description |
|---|---|---|
| System development (SYS-DEV) | 31,9 | Challenges related to system development, including analysis, procurement, requirements, construction and testing the systems and sub-systems. |
| Limited resources (LIM-RES) | 20,7 | Limitations in personnel, equipment, financial or production capabilities, as well as time for activities. |
| Project planning (PRO-PLA) | 14,7 | Challenges related to planning of activities to ensure timely completion of project. |
| Resource allocation (RES-ALL) | 11,6 | Allocation of human, physical, or financial resources, including new positions within the project. |
| Robustness (ROB) | 9,6 | Issues with robustness of system or sub-systems, e.g. stability, failures, lifetime, and repairs. |
| Technology component production (TEC-PRO) | 7,6 | Production quality and production capability challenges. |
| Organizational support (ORG-SUP) | 1,6 | Limited support for the project within an organisation. |
| Technology development (TEC-DEV) | 1,2 | Challenges due to technology performance, e.g. core material composition and component performance. |
| Technology familiarization (TEC-FAM) | 1,2 | Resource use for familiarization with the technology. |

Extending the analysis, the theme distribution for each project was investigated. A few prominent observations would be made. It was found that Test, Implementation, and Project management were prominent tasks. Based on literature, the Familiarization task was also expected to be high; however, only a single entry with this was found. The main challenge theme was found to be System development.

The rest of the identified themes did not show a clear tendency or could not be directly linked to the development with novel technology.

**Reflection on the results:**

- As paper A was published in the proceedings of a conference, the paper only partly addresses RQ1a. Paper B supplements the answer to RQ1a.
- The paper was analysed mainly by the first and second author. For a better coding reliability a re-coding could have been made.
- The data set was based on monthly reports from four of the work packages in the DEAP project. A broader analysis, including monthly reports from the other work packages in the DEAP project would provide additional information on the tasks and challenges.

### 5.2.2 PAPER B

**Title:** "*A Multi-Layered Approach to Architecture Modeling – Application on Prototypes*" (Ravn, P. M., Guðlaugsson, T. V., Mortensen, N. H.)

**Journal:** CERA – Concurrent Engineering – Research and Applications

**Contribution:** First author

**Cases:** Case 4-7

**Research Questions answered:** The paper provides an answer to research questions 1b, 1c, and 1d, and answers research question 1a together with Paper A.

- ☑ RQ1a - What are the tasks and challenges of developing prototypes with input of a novel technology?
- ☑ RQ1b – How can the combination of a new technology and a part of an existing product be understood as a prototype?
- ☑ RQ1c - How can product architectures of prototypes be modeled in a technology development setup?
- ☑ RQ1d – What are the effects of using a product architecture model representation for prototypes in technology development?

**Contribution to the research:** Paper B has three main contributions: (a) the definition of a specific type of prototype, the *technology prototype*, (b) the definition of the appertaining architecture, the *technology prototype product architecture*, and (c) the *Technology Prototype Product Architecture Tool* (the TePPAT). The technology prototype provides the answer to RQ1b, while the TePPAT provides the answer to RQ1c and RQ1d. The technology prototype was described with the following definition:

> *"Prototypes developed to investigate and demonstrate the performance of a novel technology are… … referred to as technology prototypes. These are a kind of experimental prototypes that demonstrate the principle of the use of a novel technology in part of an existing product."*
>
> (Ravn, Guðlaugsson, et al. 2015a), p. 3

The technology prototype is used to focus on implementing core functions, to which a novel technology provides a plausible solution to develop and test.

In addition, technology prototype product architecture was defined:

> *"The technology prototype product architecture will… …consist of (a) a part of an existing product architecture and an instance of the technology system… … or (b) a completely new architecture within that product field, made possible by the new technology."*
>
> (Ravn, Guðlaugsson, et al. 2015a), p. 3-4

The definitions were illustrated in Figure 43.

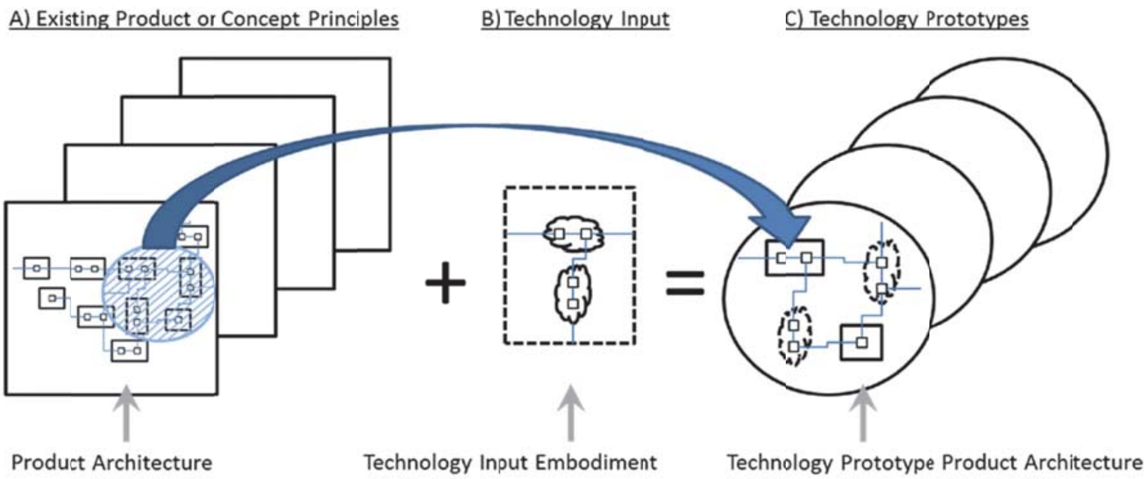


**Figure 43 - The perception of a specific type of prototype – the technology prototype [from (Ravn, Guðlaugsson, et al. 2015a)]**

The proposed tool, the TePPAT draws from the Organ Diagram (Harlou 2006), but has the following focus:

> *"The TePPAT is focused on the definition of a prototype's architecture and linked to information used in the development process, providing inputs to the refinement of the technology input."*
>
> (Ravn, Guðlaugsson, et al. 2015a) p.6

**Research method:** In the paper, an architecture modeling approach for modeling product architectures to test novel technology sub-systems was assessed. The modeling approach was based on a review of state-of-the-art literature that formed the initial versions, as illustrated in Figure 44. The TePPAT was developed through an action research approach and tested in four industrial cases arranged as a multiple-case design (Checkland & Holwell 1998; Yin 2009). The cases A-D are the cases described as cases 4-7 in Chapter 2.5.1.

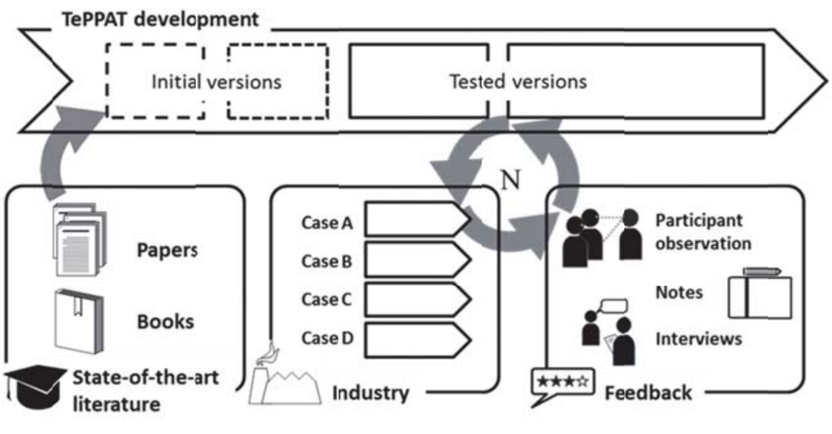


**Figure 44 - The method used to test the TePPAT. [from (Ravn, Guðlaugsson, et al. 2015a)]**

Multiple iterations were made in developing the TePPAT with feedback to revise and develop the tool.

The sources of information were:

- Informal interviews.
- Meeting notes from participating in project meetings.
- Participant observation.

**Results:** The TePPAT consists of three main sections to capture the essence of the technology prototypes, as illustrated in Figure 45.

- *Purpose* – describing the purpose of the technology prototype and the quantified success criteria.
- *Concept* – describing the main design units in the prototype architecture
- *Architecture* – describing the technology prototype product architecture.

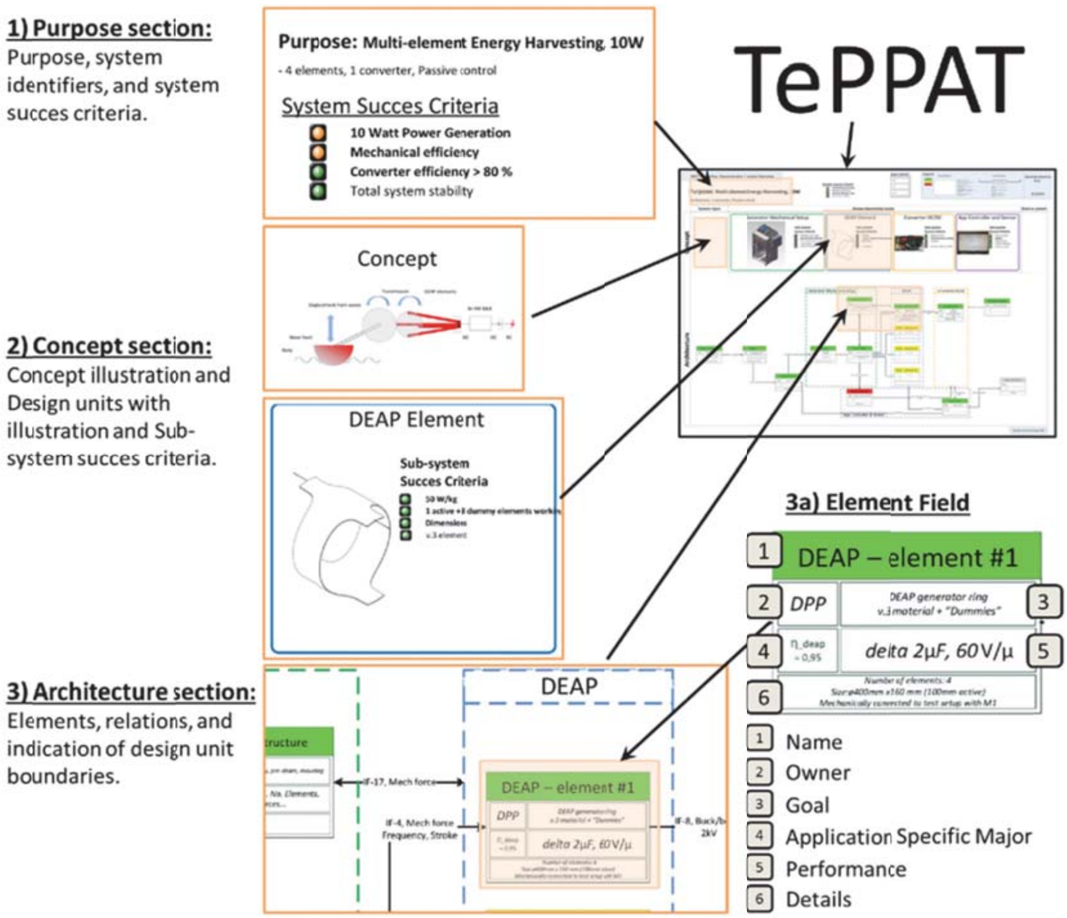


**Figure 45 - A case example of the use of the TePPAT [from (Ravn, Guðlaugsson, et al. 2015a)]**

From a conceptualization viewpoint, the Concept section contains the two sides of a concept description: the idea with, and the idea in (Hansen 2002; Hansen 2003). The Purpose section describes the idea with, and the Architecture section describes the idea in.

The use of the TePPAT was divided into four categories: reasoning why, defining the technology prototype, communication, and analyses. For these four categories, usage and effect was recorded, as illustrated in Table 9.

**Table 9 - Usage and effects in the cases [from (Ravn, Guðlaugsson, et al. 2015a)]**

| Topic | Usage | Effect | Cases |
|---|---|---|---|
| Reasoning why | Defining a shared understanding of the technology prototype. | Avoiding misunderstandings by aligning the modeling language between the stakeholders from different engineering domains. | A, B, C, D |
| | Active usage of Purpose, Concept, and Architecture sections during meetings. | Overview of the technology prototype designs.<br>Agreement on shared description of technology prototype. | A, B, C, D |
| Definition of the technology prototype | Defining purpose. | Keeping the overview during development work.<br>Keeping a steady course in the development for defining when the prototype was finished and what the level of success was. | A, B, C, D |
| | Defining concept. | Defining of the responsibilities on a general level between the teams and the main interfaces. | A, B, C, D |
| | Defining architecture. | Increasing common overview for the development team. | A, B, C, D |
| | Defining development tasks. | Supporting the project management. | A, B, C, D |
| | Identification of interfaces, elements, and functions of the technology prototypes. | Pin-pointing the key interfaces and functionalities from introducing the novel technology. | A, B, C, D |
| | Agreeing on interfaces. | Enabling resource savings.<br>Avoiding confusion. | A,B, C |
| | Abstracting detailed, technical discussions during meetings. | Enabling different engineering domains to understand each other. | A, B, C, D |
| | Defining system and sub-system tests. | Enabling verification of system and subsystem tests. | B, C |
| | Comparison of sub-system alternatives. | Clarifying system composition. | A |
| Communication | Communication of the technology prototype designs from an abstracted system level and down into details within each functional element. | Strengthening communication and discussions internally in the teams by allowing pinpointing of discussion objects. | A, B, C, D |
| | Communication to the upper management of the project regarding strategy planning and progression of the technology prototypes. | Strengthening external communication of the technology prototypes by allowing an abstracted and coherent overview of the technology prototypes. | A, B, C, D |
| Analyses | Iteratively modeling future instances of the technology prototypes ahead of building them in addition to roadmaps. | Reducing the development cost of consecutive technology prototypes by indication of what elements could be reused.<br>Increasing visibility of development strategy. | A, B |
| | Performing gap analysis. | Guiding discussions. | B, C |
| | Live update from purpose to architecture in a single view. | Increasing meeting efficiency by allowing on-the-fly changes during meeting | A, B, C, D |

**Reflection on the results:**

- The presented results were mainly qualitative as they were based on participant observation, meeting notes, and informal interviews. Quantitative measurements would provide a stronger indication of the effects of using the TePPAT.
- 16 TePPATs were defined in the four projects – additional investigation could be made on architecture principles from the use of the TePPAT.

## 5.3 Product Architecture and Production Architecture in Early Development Setting

The papers associated with product and production architecture are Paper E, Paper D, and Paper F.

### *5.3.1 Paper E*

**Title:** "*Front End Conceptual Platform Modeling*" (Guðlaugsson, T. V., Ravn, P. M., Mortensen, N. H., Sarban, R.)

**Journal:** CERA – Concurrent Engineering – Research and Applications

**Contribution:** Second author

**Case Studies:** Case 2

**Research Questions answered:** Research question 2a is answered in this paper:

☑ RQ2a: How can diverse requirements from multiple application areas be related to a product architecture defining a platform in early development stages?

**Contribution to the research:** Paper E presents the conceptual product platform (the CPP).

> *"The CPP aims to support development in the rare case when the organization lacks (1) a clearly defined market or knowledge of the market, (2) existing products to base a platform on, and (3) matured production processes."*
>
> (Guðlaugsson et al. 2014), p. 3

In the paper it is found that literature does not cover "*how to support front-end platform development within a dynamic solution space for an uncertain purpose while supporting commonality for future product families*" (Guðlaugsson et al. 2014), p. 3.

**Research method:** The research method followed in this paper was based on a case study and the research approach was based on action research. The primary data collection methods were:

- Observation.
- Field notes.
- Interviews.
- Documents from case project.

The CPP was represented in a graphical model in poster style, including the use of hand sketches.

**Results:** The CPP was tested in the DEAP project and used to provide an overview at a higher level of abstraction.

The CPP comprises the following modeling elements, which also can be seen in Figure 46:

- Application requirements: requirements for different applications, market segments, and use scenarios that clarify the needs that have to be taken into account.
- Application concepts: particular solutions, in which the application requirements are fulfilled.
- Product specifications: the needed performance of the product to fulfill the requirements of a particular application.
- Product concepts: products that are achievable by combining organ alternatives.
- Organ diagram: depicts the generic architecture of the product concepts.
- Organ alternatives: alternative means of acquiring the internal function to be provided by the organ.

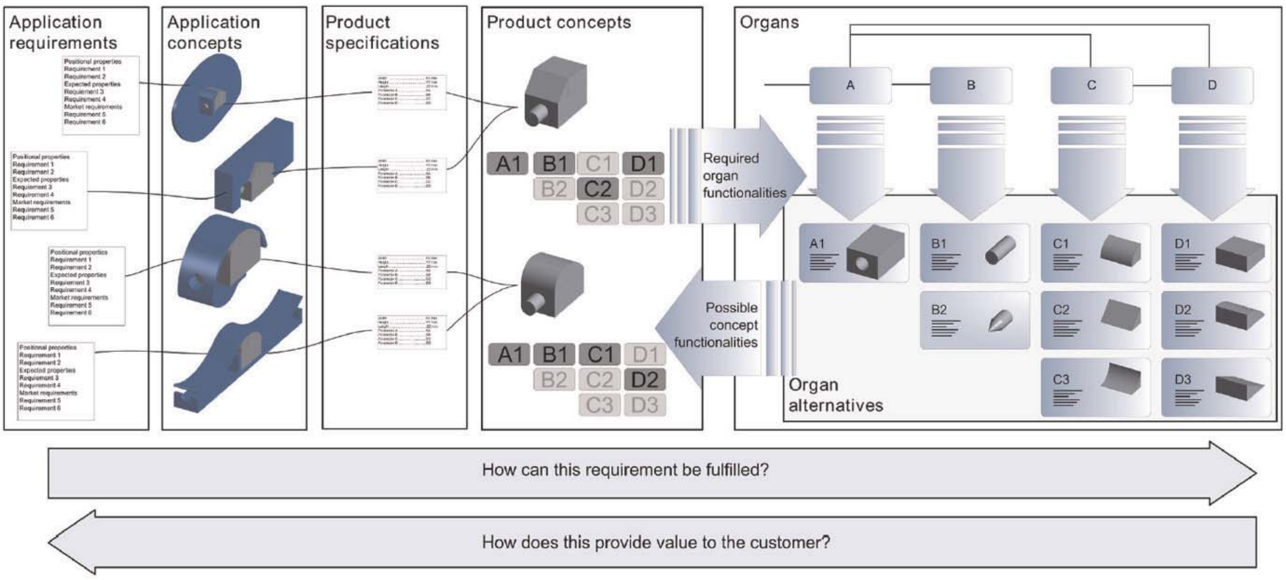


**Figure 46 - The elements of the CPP [from (Guðlaugsson et al. 2014)]**

> *"When read from left to right, the CPP aims to show how an application requirement can be met through the platform contents, while right to left reading order aims to show how platform elements can provide value to the customer."*
>
> (Guðlaugsson et al. 2014), p.5

It is argued that while the detailed part design is not part of the scope for the CPP, it allows standardization of main solutions and technologies in a portfolio. From this, the probability of commonality is increased and thus achieving greater value from technological know-how.

The CPP from the DEAP case is illustrated in Figure 47 and shows the six different elements of the CPP in use.

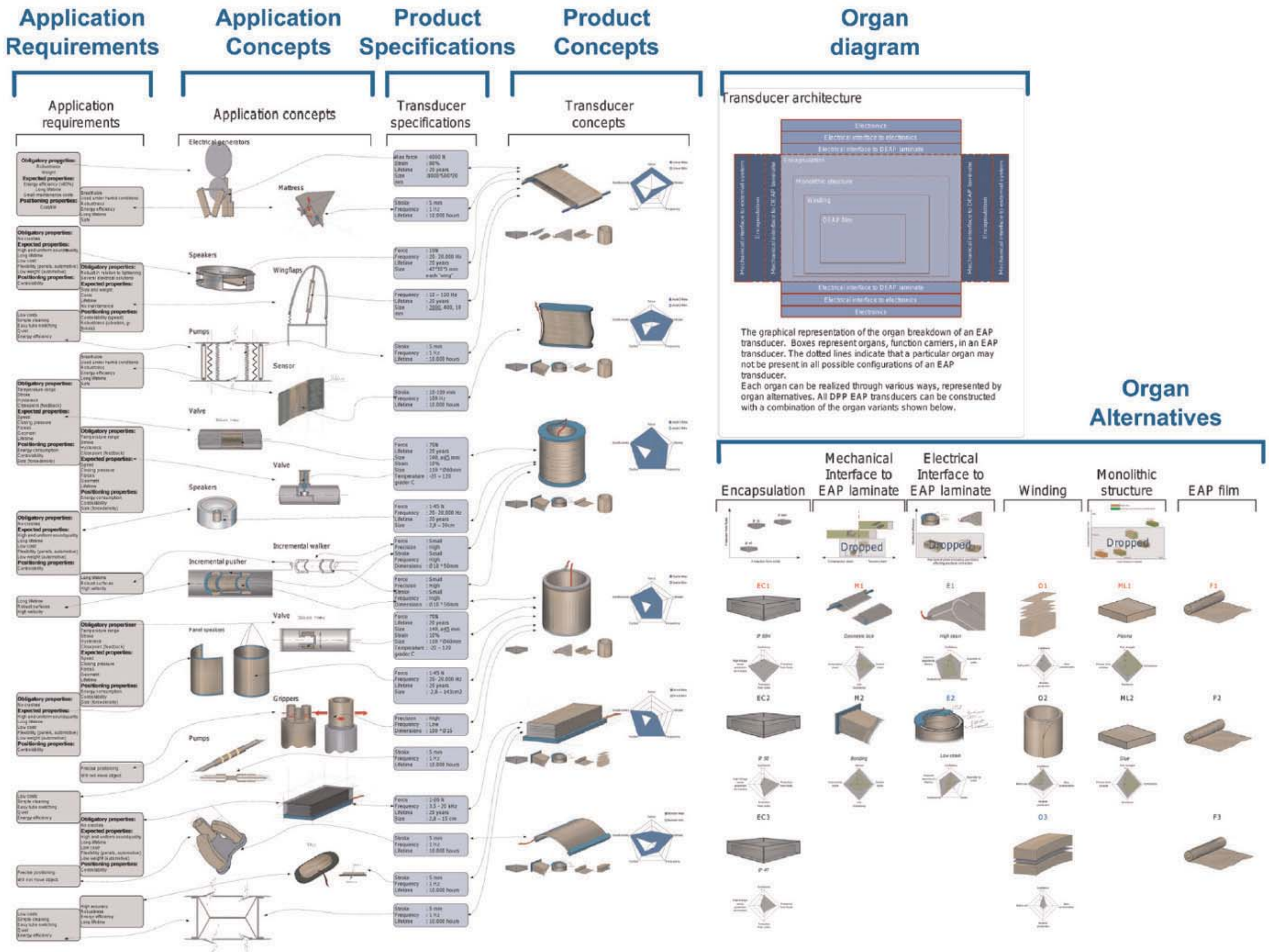


**Figure 47 - The CPP from the DEAP project [from (Guðlaugsson et al. 2014)]**

Figure 47 also illustrates how different product concepts were related to different application requirements.

> *"Multiple concepts in the CPP were able to fulfill the same application, and concept reduction was based on their ability to fulfill multiple application requirements and their sharing of organ alternatives."*
>
> (Guðlaugsson et al. 2014) p. 7

The CPP was used predominantly in physical format during meetings in the project to ensure alignment of the elements of the CPP.

Used as a communication tool, the CPP was tested with different recipients. The findings in regards to utilization dimension are presented in Table 10.

**Table 10 - Overview of findings in regards to recipients, communication form, and utilization dimension [adapted from (Guðlaugsson et al. 2014)]**

| Recipients | Communication form | Utilization dimension |
|---|---|---|
| Participants from platform development work package | A poster showing that the CPP model has been hung on the wall during meetings with other work packages | Track performance goals for organ alternatives<br>Link development tasks within the platform to application context and to other work packages<br>Provide a platform perspective during discussions on tasks within platform development<br>Decide focus of organ alternative development tasks based on design rationale<br>Evaluate the contribution of organ alternatives to the platform to make decisions on which development tasks to continue and discontinue |
| Participants from other work packages | A poster showing that the CPP model has been presented during meetings with other work packages and hung on the wall during meetings with other work packages | Present platform contents and capabilities<br>Link development work in the other work packages to the platform development to identify performance factors for platform<br>Communicate platform capabilities during concept development for key applications |
| Steering committee | Parts of the CPP model have been presented in presentations at steering committee meetings to provide an update of the progress in the development of the project | Prioritize focus areas and resources within the DNATF DEAP project<br>Evaluate platform potential and platform development work with focus on platform capabilities and feasibility of development work |
| Customers visiting DPP offices | The CPP model has been presented to visitors to DPP offices, both customers and potential customers | Present platform contents and capabilities<br>Discuss potential platform solutions for customer's application |

**Reflection on the results:**

- The product referred to in the paper is the DEAP transducer. The DEAP transducer is seen as a sub-system in Paper B.
- The paper provided a strong rationale for the development with the two reading directions: "How can this requirement be fulfilled?" and "How does this provide value to the customer?".

### 5.3.2 Paper D

**Title:** "*Visual Modelling of Pilot Production to Support Decision Making in Production Development*" (Ravn, P. M., Guðlaugsson, T. V., Mortensen, N. H.)

**Conference:** Design 2014 – 13th International Design Conference

**Contribution:** First author

**Cases:** Case 3

**Research Questions answered:** Paper D provides an initial answer to research question 2b:

☑ RQ2b: How can diverse requirements from multiple application areas be taken into regard in production architectures in early development stages?

**Contribution to the research:** Paper D was the first paper published on the work done in WP 2 on production architecture. The paper provides insight into the method by which a visual model, the production overview, was developed in the DEAP project, as well as the contents of the model.

**Research method:** The method used in this paper was as an iterative task with completion of three draft phases before a final version of the production overview. Triangulation of data forming the production overview was done by use of:

- Notes and voice recordings from interviews.
- Existing production flow charts.
- Photos and notes from walking the production.
- Participant observation in workshops.

Review and verification was done through two workshops where drafts and large format posters were used. A figure of the process can be found in Paper D.

**Results:** The result of the research was the production overview. The aims of the production overview were to:

- Identify benefits of production equipment developments and investments.
- Communicate the decisions to be made during the development of the pilot production.
- Communicate the resulting output of key processes.
- Identify where in the production process, product characteristics are realized.
- Communicate the production process design to multiple recipients at different levels in the organization.

The production overview can be seen in Figure 48 and is composed of multiple parts:

- *Vision* of the production capacity to demonstrate production scalability.
- *Production process* by past, current, and future views of the production setup (these are referred to as Production Architectures in the Production Architecture Framework in paper F).
- *Roadmap*, to illustrate the completed, current, and ongoing tasks.

- *Benefits of improvement* in a tasks-benefit matrix to illustrate the benefits enabled by development tasks.

Each of the three production process models comprised:

- *The process flow*, i.e. the process steps and their relations. Groupings of steps were indicated with shading, representing specific relations to specific machines.
- *Storage and transport* between process stations.
- *Main stations* (machines) at the bottom of each model, related to the shading in the process step groupings.
- *Resulting output*, highlighting where variants were realized.
- *Process time* for a single batch and indication of how many times faster a process can become if an upgrade is realized.
- *Critical decisions* to be made on workstations or processes with alternatives and implications noted.
- *Achieved characteristics* realized by the main stations, indicating the relation between upgrades and film characteristics.

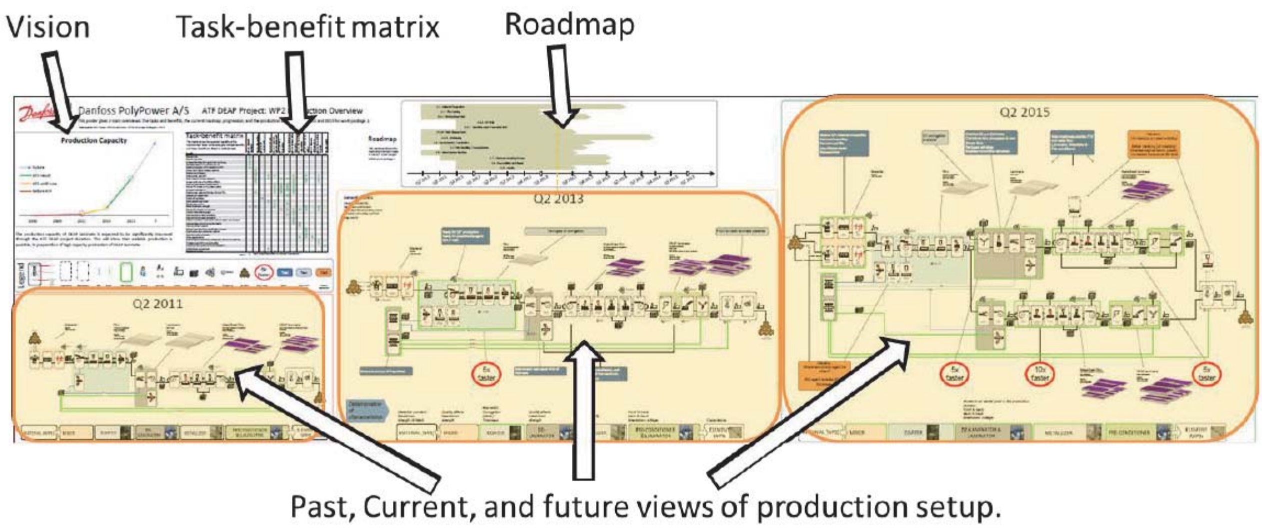


**Figure 48 - The production overview [from (Ravn et al. 2014)**

It was found that the production overview was a strong tool to create discussions and highlight flow and details. This reduced the resources required to create an accurate model of the production.

The production overview enabled the production team to:

- Show the core of the process.
- Link this to the characteristics of the DEAP film.
- Reason about future updates.
- Predict what effects changes would have.

It was observed to have a positive effect on:

- Bringing up issues regarding the production process development.

- Creating awareness about keeping ‘this and that’ in mind.
- Seeing how a change in one process would affect the production setup.

The production overview was considered to have fulfilled the aims.

**Reflection on the results:**

- As paper D was published in the proceedings of a conference, the paper only partly addresses RQ2b. Paper F expands the material presented in paper D with a deeper theoretical foundation.
- The production overview was inspired by the Generic Production Flow (Mortensen et al. 2011), however with a specific focus on situations where neither product nor production was fully defined. Additionally a high priority was on where product characteristics were realized in the production process.
- The application of the production overview was only tested in an early development setting where neither product nor production was fully defined, and not in a fully defined production setup.
- The presented model was not intended to work as a total definition of a production setup, rather provide an overview of key factors to support discussions and decision-making.

### 5.3.3 *Paper F*

**Title:** "*Modelling production architectures in the early phases of product development*", (Guðlaugsson, T. V., Ravn, P. M., Mortensen, N. H.)

**Journal:** CERA – Concurrent Engineering – Research and Applications

**Contribution:** Second author

**Case Studies:** Case 3

**Research Questions answered:** Research questions 2b is answered in this paper:

- ☑ RQ2b: How can diverse requirements from multiple application areas be taken into regard in production architectures in early development stages?

**Contribution to the research:** Paper F extends the theoretical aspect of the work initially presented in Paper D. In Paper F it is found that existing approaches in literature rely on complete definitions of products and the production system, which is not the case in early development of a production setup.

It is argued that a modeling approach, clearly showing which parts of the product and production architecture have been stabilized, and which parts of the architecture are still under development, can be beneficial. Paper F proposes a production architecture (PA) modeling framework intended for use in the early stages of product development.

The PA modeling framework presents:

> *"… information on the PA from three distinct perspectives. The structure… … the capabilities… … the expansions…"*
>
> (Guðlaugsson et al. 2015), p. 9

The three perspectives, *structure*, *capabilities*, and *expansions*, answer the questions "What is it?", "What can it do?", and "What should it be able to do in the future?", respectively.

**Research method:** The contents of the PA framework were derived from a Google Scholar literature search using combinations of the search terms "manufacturing", "manufacturing system", "production", "production system", "technology", "process", "design", "development", "selection", and "architecture".

The PA framework was tested in the DEAP project, WP 2 specifically, to evaluate whether it would be practical to use, whether critical parameters and decisions could be identified, and whether communication of these would be facilitated by the framework. Interviews and direct observation were used to evaluate the framework.

**Results:** Based on the literature search, requirements for information about the PA were found (please see Table 11).

**Table 11 - Relevant factors that form the requirements for the PA framework contents [adapted data from (Guðlaugsson et al. 2015)]**

| Perspective | Relevant factors |
|---|---|
| Structural elements (what is it?) | The constituent elements, such as sub-systems, the equipment and workstations (Matt 2008), and structure, where the structure is the organization of the physical elements and their relations (Hubka & Eder 1988).<br>Links from a production system's elements and functions to elements of the product architecture through dispositional effects (Olesen 1992).<br>Indication of the choice of production technology; a key determinant for achievable functionality of the production system and investments required to implement the production system (Skinner 1985; Farooq & O'Brien 2012). |
| Functional elements (what can it do?) | Product flexibility, as it is the capability to produce new product variants economically and quickly (Jain et al. 2013; Sanchez 1995), which is necessary when the product architecture description is not complete—the aim should be to obtain the right flexibility (Matta et al. 2000; Boyle et al. 2002).<br>Volume flexibility, as it is the range of production volume within which the production system can profitably produce products and important in new product introduction (Negahban et al. 2014).<br>Processing and setup times, batch sizes, and partially produced goods, as these greatly affect the production system performance (Matt 2008; Suh et al. 1998; Russel & Taylor 2011).<br>Product differentiation points, as these affect product design as well as product and volume flexibility (Yang & Burns 2003).<br>Indication of obtainable quality, as quality is generally prioritized over flexibility and should be considered during production system development (Inman et al. 2013). |
| Expansions (what should it be able to do in the future?) | Production volume scaling, as moving from a laboratory setting to industrial production scale can require rigorous experiments on industrial production equipment to identify performance parameters and improve obtainable quality (Galagan et al. 2011; Taguchi et al. 2004).<br>Capabilities, as these can be expanded upon to enable delayed investment for capabilities that are not needed until later on—interfaces between sub-systems are central to facilitating capability expansion (Jain et al. 2013). |

The three perspectives are represented in Figure 49. Three PA models were created in the DEAP project to test the PA framework.

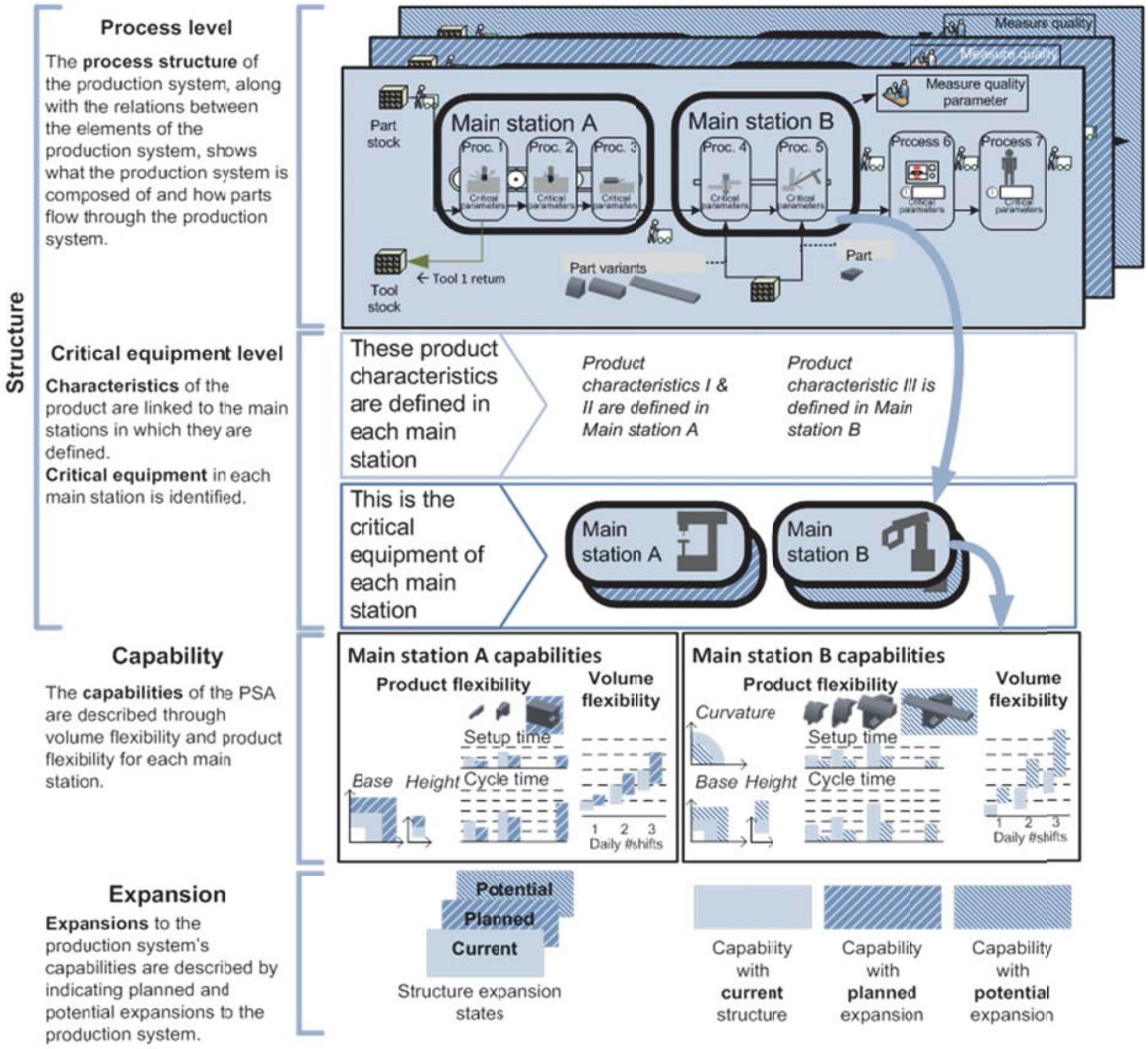


**Figure 49 - The three perspectives in the PA framework [from Paper F]**

The following statements were recorded from the project participants (from (Guðlaugsson et al. 2015), p.14):

- "Hearing how the production team was able to use the models for communication—internally and externally—showed me that it was a good solution. The production team could use it and explain it and use it to explain to others what the production was all about."
- "The information on the production system that was hidden inside our minds has been visualised in the models"
- "It's good to use with people that do not have the in-depth understanding of what our production system is about"
- "The models give us an overview of the solutions and where potential changes may affect the following processes—do they have a detrimental effect on the other processes?"
- "We needed to communicate what is the activity, what is the process, and what is critical—this is captured in the production architecture models"

The application of the PA models in the DEAP project was used to validate the perspective requirements presented in Table 11. The case study results indicate that:

- The framework facilitated identification of critical PA parameters.
- The framework captures and presents implicit and explicit decisions.
- The resulting PA models facilitated dialogue by confronting recipients with a concrete perspective.
- The framework is designed to be implemented in a dynamic, uncertain, environment at an early phase of development.

**Reflection on the results:**

- The findings in Paper F complement Paper D in answering RQ2b, however more thoroughly.
- Testing the framework was limited to a single case, but may be relevant to other firms and other industries.

## 5.4 ARCHITECTURE COHERENCE AS A BASIS FOR PRIORITIZATION

The paper associated with the topic is Paper C.

### *5.4.1 PAPER C*

**Title:** "*Identification of critical technology building blocks*" (Ravn, P. M., Mortensen, N. H., Hvam, L.)

**Journal:** Submitted to journal

**Contribution:** First author

**Cases:** Case 8

**Research Questions answered:** The research questions answered in this paper are 3a and 3b:

- ☑ RQ3a: What structure can be identified for coherent architectures to enable a complex system understanding?
- ☑ RQ3b: How can architecture coherence be used to identify and prioritize critical areas in the development?

**Contribution to the research:** Paper C has three main contributions: (a) the definition of *critical technology building blocks*, (b) a *3-step framework* for identifying these by means of property reasoning, and (c) the definition of *property target chains* and *property delivery chains*.

The critical technology building blocks are defined as:

> *"… those essential for increasing key product properties."*
>
> (Ravn et al. 2015)

The framework to identify critical technology building blocks is consisting of three steps:

- Step 1: Creating the portfolio overview – where the base structure is described on multiple layers.
- Step 2: Assessing the system elements – where the contents of the overview are assessed.
- Step 3: Reasoning about properties – where the desired properties are projected down through the portfolio overview.

Two types of property chains are used. Property Delivery Chains (PDCs), bottom-up, and Product Target Chains (PTCs), top-down:

> *"PDCs track the deliveries made based on the solutions chosen. One solution may contribute with multiple properties. PTCs are used… … to track properties down to CTBBs."*
>
> (Ravn et al. 2015)

**Research method:** In this paper, the DRM approach was used, from Research Clarification (RC) to initial Descriptive Study II (DS-II). A literature study was conducted in two parts, one for state-of-the art within modeling approaches, and one for theoretical base for the framework. The base of the framework was created based on literature and the framework was tested in the concluding phases of the DEAP project. Finally, the framework was evaluated by four key persons from the project.

**Results:** A number of challenges were extracted from literature:

- By splitting technology development and product development in the organization, there is a risk of inefficient transfer of technology and lack of synchronization ((Wood & Brown 1998; Lakemond et al. 2007; Nobelius 2004; Holt 1991).
- A large part of the value chain may have to be developed from scratch when a novel technology is used for definition of new products (Wood & Brown 1998; Tryson & Kiil 2010).
- There are disconnects between the strategies of the business and where the money are spent (Cooper et al. 2001).
- Resources need to be spent with the best possible chance of progression on the right tasks (Mankins 2009a).
- Increasing high level of complexity and high level of technical novelty in products affect technology integration (Iansiti 1995).
- There is a high dependence on the competence and the initiative of individual managers and engineers (Holt 1991; Mankins 2009b).

Requirements for the framework to identify critical technology building blocks were formed based on these. The framework should enable R&D managers to:

- Identify a structure that can describe the relation between the products and technologies in the company portfolio, as technologies are developed with an intended use in the organization.
- Assess the development, as it is critical for senior management to be able to choose between alternatives (Mankins 2009a).
- Trace product properties through the value chain, as these are key to positioning on the market (Mørup 1993).
- Identify the technologies that are the main contributors to the next level of performance within a certain property as these can be defining for the technology strategy.

The three-step framework was based on findings in literature. In Step 1 a portfolio overview is created. It follows a diabolo structure (Erens 1996), as illustrated in Figure 50. Within a tier of the structure, two dimensions are depicted: the product dimension and the technology dimension. The product dimension includes from the top: *variants*, derived from a *product family*, formed by *components*. The technology dimension includes two views on technology: product and production.

In Step 2 the elements of the overview were assessed, and in Step 3, critical technology building blocks were identified, by means of product target chains (see Figure 51).

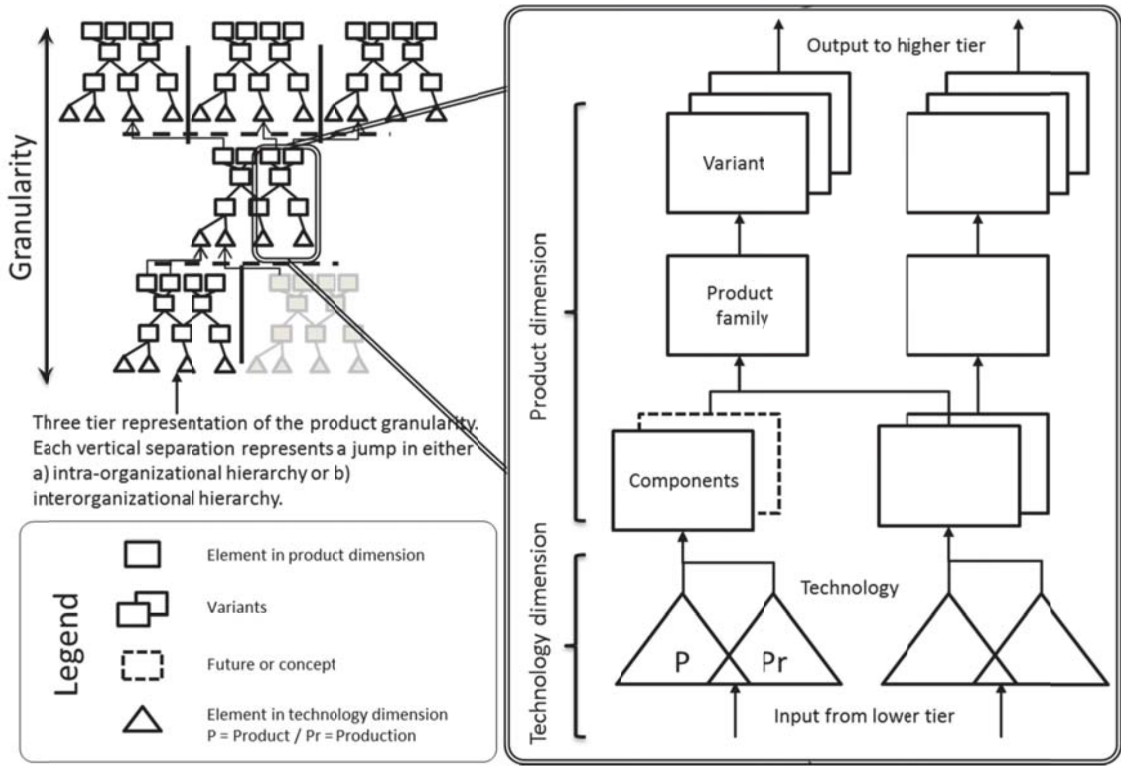


**Figure 50 - The entity-relation structure proposed [from (Ravn et al. 2015)]**

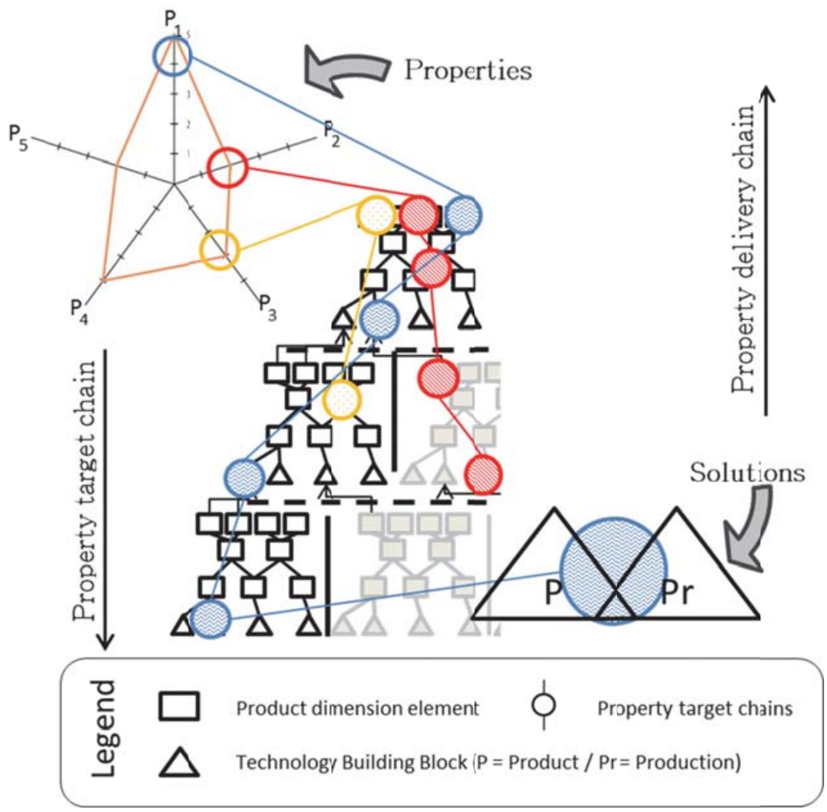


**Figure 51 - The use of property target chains and property delivery chains [from (Ravn et al. 2015)]**

With the use of the framework in the DEAP project it was illustrated that critical technology building blocks could be identified by use of property target chains. Two critical technology building blocks were identified.

The following statements were given to the use of the framework (from (Ravn et al. 2015), p. 17):

- "I realize that some tasks form around a whole new technology by themselves."
- "The framework is really strong for cutting to the bone for the next step (of development)."
- "We need to discuss whether some technologies are product or production related."
- "The framework is best suited for a top-down approach."
- "For the technological decisions, we now have an idea of where to focus."
- "By tracking the value propositions we can see the impact."

**Reflection on the results:**

- The framework presents a structured approach to identify critical technology building blocks.
- It is assumed that for both technology push and market pull, potential products in which the technology can be integrated, can be identified.

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*"This is the beginning of the end."*
- Charles-Maurice de Talleyrand, 1812

# 6 Conclusion

*This chapter concludes the thesis by going through the research and the contributions herein. The research questions are answered, the main contributions highlighted, the research evaluated, the limitations discussed, and the research impact evaluated.*

## 6.1 Answering the Research Questions

In Chapter 2.1, research questions covering three main areas were posed for this research. This chapter is used to answer these to elaborate the argumentation from the appended papers. The chapter is split into three main areas: 1) Product architecture instances for prototypes testing novel technology 2) Product architecture and production architecture in early development setting, and 3) Architecture coherence as a basis for prioritization.

### 6.1.1 *Product Architecture Instances for Prototypes Testing Novel Technology*

The research questions RQ1a-1d have been answered through Paper A and Paper B.

**RQ1a** - What are the tasks and challenges of developing prototypes with input of a novel technology?

The first research question has been answered mainly through Paper A. The thematic analysis of the monthly reports resulted in both tasks and challenges being identified. The monthly reports came from four teams developing prototypes with input of a novel technology. In the analysis, 17 main themes for tasks were identified, based on 683 task entries. Nine main themes for challenges were identified from 250 challenge entries.

Based on literature findings it was expected that the occurrence of *Testing* tasks and *Project management* should be high; as well as the occurrence of a specific task, familiarization was expected.

The findings from the analysis verified a high occurrence of tasks related to *Testing* and *Project management*. However, the task *Familiarization* was only identified once, which was against suggestions from literature. For the challenges, *system development* was prominent.

The main tasks and challenges can be found in Table 7 and Table 8.

**RQ1b** – How can the combination of a new technology and a part of an existing product be understood as a prototype?

Research question 1b was answered through Paper B. The research forming the basis for Paper B was linked to the tasks of prototype development with the DEAP technology.

It was found that the current vocabulary did not describe the situation at hand: integration of a novel technology into a prototype with origins from a specific product domain. To describe the combination of a novel technology and a part of an existing product as a prototype, the following type of prototype was proposed:

Technology prototype - a kind of experimental prototype that demonstrates the principle of the use of a novel technology as part of an existing product.

Linked to this technology prototype is a type of architecture:

Technology prototype product architecture - consisting of (a) a part of an existing product architecture and an instance of the technology system or (b) a completely new architecture within that product field, made possible by the new technology.

**RQ1c** - How can product architectures of prototypes be modeled in a technology development setup?

The TePPAT modeling approach was suggested in Paper B as a 2D representation to document the product architectures of the technology prototypes: the technology prototype product architectures.

The focus of the TePPAT was the definition of a prototype's architecture and linked to information used in the development process, providing inputs to the refinement of the technology being tested.

The TePPAT consisted of the following three sections:

- *Purpose* – describing the purpose of the technology prototype and the quantified success criteria.
- *Concept* – describing the main design units in the prototype architecture
- *Architecture* – describing the technology prototype product architecture.

The three sections can also be described from a conceptualization viewpoint (a description of the *idea with* and the *idea in* a concept), where the purpose section describes the *idea with*, the concept section describes both the *idea with* and the *idea in*, and the architecture describes the *idea in*.

**RQ1d** – What are the effects of using a product architecture model representation for prototypes in technology development?

Research question 1d was answered through Paper B. It was found that the use of the product architecture model representation, in the form of the TePPAT, could be classified under four topics:

- Understanding why.
- Definition of the technology prototype.
- Communication.
- Analyses.

The effects of using the TePPAT model representation were, taken from Table 9, captured qualitatively:

- Avoiding misunderstandings by aligning the modeling language between the stakeholders from different engineering domains.
- Overview of the technology prototype designs.
- Agreement on shared description of technology prototype.
- Keeping the overview during development work.
- Keeping a steady course in the development for defining when the prototype was finished and what the level of success was.
- Defining of the responsibilities on a general level between the teams and the main interfaces.
- Increasing common overview for the development team.
- Supporting the project management.
- Pin-pointing the key interfaces and functionalities from introducing the novel technology.
- Enabling resource savings.
- Avoiding confusion.
- Enabling different engineering domains to understand each other.
- Enabling verification of system and subsystem tests.
- Clarifying system composition.
- Strengthening communication and discussions internally in the teams by allowing pinpointing of discussion objects.
- Strengthening external communication of the technology prototypes by allowing an abstracted and coherent overview of the technology prototypes.
- Reducing the development cost of consecutive technology prototypes by indication of what elements could be reused.
- Increasing visibility of development strategy.
- Guiding discussions.
- Increasing meeting efficiency by allowing on-the-fly changes during meeting.

### 6.1.2 *PRODUCT ARCHITECTURE AND PRODUCTION ARCHITECTURE IN EARLY DEVELOPMENT SETTING*

Research question 2a was answered through Paper E.

**RQ2a** – How can diverse requirements from multiple application areas be related to a product architecture defining a platform in early development stages?

It was found that a specific structure of modeling elements, realized by the CPP, was able to relate the requirements from multiple application areas to the product architecture. The modeling elements were, as illustrated in Figure 47:

- Application requirements.
- Application concepts.
- Product specifications.
- Product concepts.
- Organ diagram.
- Organ alternatives.

The rationale for reading the CPP assisted the argument for the relation from multiple application areas to production architecture:

- Reading from left to right: How can this requirement be fulfilled?
- Reading from right to left: How does this provide value to the customer?

Research question 2b was answered through Papers D and F.

**RQ2b** – How can diverse requirements from multiple application areas be taken into regard in production architectures in early development stages?

In Papers D and F the Production Architecture framework was proposed. Part of the framework answers research question 2b.

Based on literature, three categories of requirements were defined for the framework, corresponding to giving an answer to the questions: “What is it?”, “What can it do?”, and “what should it be able to do in the future?”

From this, the Production Architecture was constructed, based on three main perspectives: the *structure*, the *capabilities*, and the *expansions*.

Specifically providing the answer to RQ2b is the capabilities perspective, which describes what the Production Architecture framework can do through modeling the product variants produced, the product flexibility, and volume flexibility for each main station.

### *6.1.3 ARCHITECTURE COHERENCE AS A BASIS FOR PRIORITIZATION*

Research question 3a and 3b were answered through Paper C

**RQ3a** – What structure can be identified for coherent architectures to enable a complex system understanding?

Based on the architecture work done in relation to the application (the TePPAT), the product (the CPP), and the production (the PA framework) a framework for identification of critical technology building blocks was developed. The framework was developed on the basis of an understanding of the coherence between the architectures and the value chain defined in the case company.
The framework consisted of three steps. Step one concerned the construction of an entity-relation structure for the coherent architectures.
The structure spanned multiple tiers of a value chain and within a tier of the structure, two dimensions are depicted: the product dimension and the technology dimension. This was illustrated in Figure 50. The product dimension includes from the top: *variants*, derived from a *product family*, formed by *components*. The technology dimension includes two views on technology: *product* and *production.*

**RQ3b** – How can architecture coherence be used to identify and prioritize critical areas in the development?

Steps 2 and 3 of the framework for identification of critical technology building blocks give the answer to research question 3b. In step 2 the elements of the structure are assessed with a given assessment method. In step 3, property-based reasoning is used to identify critical technology building blocks. It is the claim in Paper C that the identification of critical technology building blocks supports identification and prioritization of critical areas in the development.

## 6.2 Main Contributions

The main contributions of this research are claimed to be within three areas. These are linked to the areas identified in the ARC diagram in Chapter 2.2.1.

- The definition of *technology prototype* – a specific type of prototype which demonstrates the principle of the use of a novel technology in part of an existing product.
- The definition of *technology prototype product architecture* – a product architecture of the technology prototypes.
- The *TePPAT* modeling approach for modeling instances of architectures in prototypes with novel technology.
- Identification of an *entity-relation structure* to encompass coherent architectures.
- The definition of *critical technology building blocks* – building blocks on a technology-level that are essential for increasing key product properties.
- A *three step framework* for identification of critical technology building blocks.

## 6.3 Evaluation of Research

The papers describe tools or frameworks that have been developed and tested. These papers will be evaluated after the validation square, presented in Chapter 2.4.4. Papers A and B and Papers D and F are presented together as these are based on the same cases.

### 6.3.1 *Evaluation of Paper A and Paper B*

The contribution presented in Paper B is a tool for modeling and managing technology prototype product architectures. Paper A is supporting the identification of tasks and challenges in the technology development context.

(1) **Individual constructs:** the individual constructs were based on literature from architecture development and prototype development. Although introducing new concepts for understanding prototypes and architectures in a technology development context, the acceptance of the proposed constructs are indicated through peer-reviews and by the feedback from the case study participants.

(2) **Internal consistency:** the constructs of the modeling formalism are based on the theory presented in Chapter 3. Although new terminology is proposed, the internal consistency is achieved through basing the tool on widely accepted theories e.g. Theory of Technical Systems and Theory of Domains.

(3) **Appropriateness of the example problems:** the four cases presented for application of the tool all shared the same technology, the DEAP technology. The example problem is considered relevant for the testing as these are also the originators of the tool.

(4) **Useful outcome:** the contribution of the paper is a graphical architecture modeling tool, the TePPAT. Qualitative results from using the TePPAT was captured in Table 9 in Chapter 5.2.2. Here, the effects obtained from using the TePPAT in different situations illustrate the useful outcome of applying the tool.

(5) **Link achieved usefulness to applied method:** no other competing approaches were used for the same purpose in the four projects in which the TePPAT was tested. Furthermore, the usefulness was also reported from meetings where the researcher had not participated himself.

(6) **Usefulness beyond example problems:** The approach was tested in four projects running concurrently and each going through three iterations of prototype development with the same technology. These are illustrated in Table 2 in Chapter 2.5.1. Although providing multiple cases and drawing upon these, this is only a small part of the way to illustrate usefulness beyond the example problems.

### 6.3.2 *EVALUATION OF PAPER C*

The contribution presented in Paper C is a framework suggesting three steps for identifying critical technology building blocks. The framework was tailored to support companies in technology development with the need to identify next development steps.

(1) **Individual constructs:** the individual elements of the presented framework were created from literature from architecture and technology research. This provided a basis for deriving individual elements with good rigor.
(2) **Internal consistency:** the framework presents individual constructs based on literature. Although new terminology is proposed, the framework is based on accepted structures found in engineering design and technology development literature.
(3) **Appropriateness of the example problems:** the paper only reports on one case of application. However, the internal constructs of the framework were in agreement with the industrial application.
(4) **Useful outcome:** the presented framework was initially tested in the project and individual statements, as well as use of the framework. The participants in the workshop were able to use the framework for identifying critical technology building blocks.
(5) **Link achieved usefulness to applied method:** statements from users of the tool link the usefulness partially to the framework.
(6) **Usefulness beyond example problems:** a gap in literature was identified on how to operationally identify these technology building blocks. Other than the single case, no other cases were tested with the framework.

### 6.3.3 *EVALUATION OF PAPER D AND PAPER F*

As Paper D and Paper F are based on the same case study and supplement each other in the contribution, the two are evaluated together. The papers describe the Production Architecture framework.

(1) **Individual constructs:** the individual constructs of the framework were based on a literature search about what these should include. Therefore, the individual constructs are assessed to be good.
(2) **Internal consistency:** the constructs of the formalism was based on literature. Only limited new terminology was introduced. Rather, the context in which the tool was tested differentiated as being in early development, rather than mature development.
(3) **Appropriateness of the example problems:** the framework was used in a single case only. Paper D was used as a first probing of the problem and later expanded into Paper F, when appropriateness of the example problem was evaluated to be good.
(4) **Useful outcome:** the outcome of the tool was indicated to be useful, based on statements from users.

(5) **Link achieved usefulness to applied method:** the Production Architecture framework was used when the existing modeling approach was incapable of communicating the intended plans for the production setup in regards to capabilities and expansions. Therefore the link of usefulness to the framework can be accepted.
(6) **Usefulness beyond example problems:** the Production Architecture Framework was not tested in other cases. However, the company was in a situation which many other technology developers can find themselves in, which would support acceptance of the framework.

### 6.3.4 *Evaluation of Paper E*

The contribution in Paper E was the tool to model a conceptual product platform.

(1) **Individual constructs:** the individual constructs of the tool were building on the PFMP approach (Harlou 2006). In addition, well known theories, such as Theory of Domains was applied.
(2) **Internal consistency:** the CPP consists of a number of areas that are all found in literature.
(3) **Appropriateness of the example problems:** the paper only reports on one case of application. However, the company situation, with the need to understand the architecture of the transducer, as well as linking the requirements from customers to the technologies, makes the example problem appropriate.
(4) **Useful outcome:** the outcome was stated in Table 10 in Chapter 5.3.3.
(5) **Link achieved usefulness to applied method:** As no other approach was applied with the same purpose as the CPP tool, usefulness can be linked to the applied method.
(6) **Usefulness beyond example problems:** the framework was not tested cases other than the DEAP project. However, the mind-set of "How can the requirement be fulfilled?" and "How does this provide value to the customer?" is similar to what has been observed in other projects.

## 6.4 Evaluation of Research Impact

The evaluation of the research is concluded with an evaluation of the research impact. The research impact will be assessed in two areas: academic and industrial.

### 6.4.1 *Academic Impact*

The academic impact relates to the areas highlighted as areas of contribution in the ARC model presented in Chapter 2.2.1. The academic impact has contributions within:

**Technology integration**

The research presented in Paper B with the TePPAT contributes to the area of technology integration. The contribution lies in the definition of technology prototypes and technology prototype product architecture to describe integration of novel technology into prototypes. The tool was essentially developed to support a development situation.

**Product and production architecture**

As part of the research, product architecture and production architecture were also included as modeling approaches through the TePPAT, the CPP and the PA framework (Paper B and Papers D-F).

As described in Chapter 1.2, there are plenty of contributions to architecture work in mature development settings. However, there is a lack of architecture approaches to support the work done in early development settings. Despite contributions being found on technology platforms (Levandowski et al. 2012), no contributions have been found in literature by the author during literature searches.

The TePPAT describes product architectures of technology prototypes and provides a means to tie these to the success criteria for the technology prototypes.

The CPP describes a Conceptual Product Platform, and includes an organ diagram to represent the architecture of a sub-system (the Transducer architecture illustrated in Figure 47).

The Production Architecture framework provides arguments for the inclusion of structure, capability, and expansion in the modeling of production setups in early development stages.

**Technology prioritization**

The research presented in Paper C extends the knowledge in the area of technology prioritization through the identification of critical technology building blocks. While the structure proposed in the paper resembles the diabolo structure (Erens 1996), and combines this with a two-part view on technology (product and production), the multi-level structural description also provides an understanding of the value chain for a technology under development.

### *6.4.2 Industrial Impact*

The industrial impact of the research is here discussed, based on the main contributions presented in Chapter 6.2.

The TePPAT is a hands-on tool that has been applied in four projects over a period of 30 months. It represents a modeling tool that can aid in the definition and management of architectures for technology prototypes. The tool supports definitions of purpose, concept, and architecture to guide the development through the stages of design, build, and test.

The framework for identification of critical technology building blocks is an operational framework consisting of three main steps to creating an entity-relation overview of product and technology elements on multiple levels of a value chain, assessing the elements, and utilizing property-based reasoning to identify critical technology building blocks. The identification of these will enable the organization to prioritize the tasks in the development.

## 6.5 Limitations to the Research

The research presented in this thesis has a number of limitations. These will be covered here.

**Single and unique project**

As this PhD project followed one, single case in-depth, limited application can be argued. Most of the papers present contributions built on single case application. Paper B, however stands out in having been tested in the four application projects in the DEAP project over three iterations. Although the tools and frameworks in the research have been tested in industry, further research will need to be done in order to fulfill a claim of transferability.

On the matter of breadth versus depth: the researcher has been deeply involved in the DEAP project and thus, the results presented may not have been achieved with more projects and less amount of focus for each. This is supported by the statements that evidence from multi-case design can be considered more robust (Herriott & Firestone 1983), but cannot usually satisfy the rationale from single case design (Yin 2009).

**The unavoidable subjectivity**

The research in this project has been carried out with involvement in an industrial technology development project. The research has been done *in* action, rather than *about* action (Coughlan & Coghlan 2002). This can be argued to give a higher degree of subjectivity. However, the use of action research has provided a depth to the project, which gave the opportunity to obtain 'hard to come by' knowledge.

**Partial implementation of approaches**

The tools and frameworks presented in this research were developed as support to the needs of the industrial project. This meant that there was a specific need. As the development of the tools and frameworks were assessed to be useful, they only underwent partial implementation. This corresponds to initial descriptive study II (Blessing & Chakrabarti 2009). Only having had a single main project to follow has meant that an emphasis has been put on the internal validity of the tools and frameworks.

*"Would you tell me, please, which way I ought to go from here?"*
*"That depends a good deal on where you want to get to," said the Cat.*
- Alice's Adventures in Wonderland, Chapter 6

# 7 Further Research Suggestions

The previous chapters presented the main contributions of the PhD project.

This chapter suggests areas for further research.

The frame setup of this PhD project has required a lot of work to support the DEAP project in addition to completing the PhD. Especially, the participation in the four application projects in the DEAP project have required a high amount of involvement for support and investigation. Therefore, all opportunities could not be pursued. The following areas are proposed for further research:

**Principles for architecting in technology development**
A number of approaches have been proposed in this research on how to model architectures in different areas of technology development. A suggestion for further research would be an investigation of the architecture *principles* which can support the development of a new technology. The observations leading to this suggestion originate from the four application projects in Paper B.

**Study a larger pool of projects**
The tools and frameworks from this research were based on the DEAP project only. Testing the tools and frameworks on more cases can provide data on how the tools behave, e.g. when the project team composition or setup is changed or when the type of technology is varied.

**Transferring architectures from technology development to product development**
Product and production architecture approaches found in mature development have been adapted for application in technology development. The context in which this research has been carried out has been technology development. Therefore, further consideration would be a situation where the architecture approaches proposed in this thesis were used in a transition phase from technology development to a mature development of new products.

**Linking prototype architectures to a reference architecture**
Technology prototype product architectures were presented in Paper B. These represent a system consisting of structure taken from an existing product area combined with elements from the novel technology. Linking these architectures to a reference architecture may bring further knowledge to the technology developer of how the diverse needs and system requirements are related to the technology.

**Longitudinal study of tasks and challenges**

The tasks and challenges study of 138 monthly reports presented in Paper A, corresponding to a period of three years, gave an insight into what could be expected in technology development. Following a technology with such reports on tasks and challenges over a longer period, i.e. from technology development and into product development phases, would give greater insight into how tasks and challenges change in different development contexts.

*"'Contrariwise,' continued Tweedledee, 'if it was so, it might be;*
*and if it were so, it would be: but as it isn't, it ain't. That's logic.'"*
- Lewis Carroll: Through the Looking-Glass (1872)

# 8 Concluding Remarks

With the conclusion of this thesis, my journey through this PhD project comes to an end. One of the great experiences that I will take with me from this part of my life is the once in a lifetime chance to become a part of a technology test and evaluation project *as a researcher*. It has been a pleasure working with and learning from current and upcoming researchers and industry professionals within the many engineering fields touched upon in the Innovation Fund Denmark DEAP project.

The three years have presented me with a number of great experiences which will remain with me for the rest of my life. These, along with the increased knowledge and insight into engineering design, architectures, and technology development have influenced the way I perceive the field. Instead of uncertainty, one should see the possibilities for learning. Instead of problems, one should see possibilities.

Would I have done *some* things differently? Definitely. However, I hope that you can use the material presented in this thesis for projects of your own.

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# 10 APPENDICES

The papers that make up the research presented in the main chapters of the thesis are appended in this chapter.

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## 10.1 PAPER A: TASKS AND CHALLENGES IN PROTOTYPE DEVELOPMENT WITH NOVEL TECHNOLOGY – AN EMPIRICAL STUDY

Published in Proceedings of ICED 2015, July 2015

Authors: Ravn, P.M., Guðlaugsson, T.V., Mortensen, N.H.

**Abstract**
This paper presents a thematic analysis of 138 monthly reports from a joint industrial and academic project where multiple prototypes were developed based on the same technology. The analysis was based on tasks and challenges described in the reports by project managers over a period of three years. 17 task themes and 9 challenge themes were identified. It was found that test, implementation, and project management were prominent tasks. Familiarization with the technology was found to a very little degree, which was in opposition to literature. The main challenge was found to be system development. It was found that the predominant tasks and challenges are distributed over long periods of time, rather than in chunks linked to a specific development phase.

**INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15**
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

# TASKS AND CHALLENGES IN PROTOTYPE DEVELOPMENT WITH NOVEL TECHNOLOGY – AN EMPIRICAL STUDY

**Ravn, Poul Martin; Guðlaugsson, Tómas Vignir; Mortensen, Niels Henrik**
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## Abstract

This paper presents a thematic analysis of 138 monthly reports from a joint industrial and academic project where multiple prototypes were developed based on the same technology. The analysis was based on tasks and challenges described in the reports by project managers over a period of three years. 17 task themes and 9 challenge themes were identified. It was found that test, implementation, and project management were prominent tasks. Familiarization with the technology was found to a very little degree, which was in opposition to literature. The main challenge was found to be system development. It was found that the predominant tasks and challenges are distributed over long periods of time, rather than in chunks linked to a specific development phase.

**Keywords**: Technology, Early design phases, Project management, Development tasks, Challenges

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## 1 INTRODUCTION

Application of novel technology is regarded as one of the ways that companies can keep ahead of their competitors (Baughn and Osborne, 1989; Iansiti, 1995). Technology developers can benefit from the knowledge of lead companies that implement the technology in pre-development phases, thus increasing the knowledge about the technology in use. In such a case, a multi-prototype development strategy can be chosen, where multiple prototypes are developed sequentially to test the technology in different performance areas.

Early inclusion of companies at an early stage of technology development can be obtained through the use of prototypes. This will allow the benefits and principles of integration into a product system to be investigated and facilitates familiarization with the technology. However, there are great uncertainties at such an early stage, both regarding technology performance and appropriate lead applications (Baughn and Osborne, 1989) as the technology is still under development.

The aim of this paper is to investigate the tasks and challenges in a technology development project, from the point of view of the product developer in a technology transfer setting. The specific setup is where technology developer and product developer work together in the development of a prototype displaying the benefits of the technology in a product from the portfolio of the product developer. In this particular context, the technology was introduced to product developer at a very early stage (TRL 2-3).

As part of a research program this paper seeks to answer the following research questions (RQ):

- RQ1: What are the development tasks and challenges when building prototypes with sub-systems based on novel, advanced technologies, concurrently with the technology being developed?
- RQ2: How does early test of a technology at low technology readiness level affect the tasks and challenges?
- RQ3: How are the tasks and challenges found distributed over time in the projects?

## 2 METHODOLOGY

The overall methodology used for this paper is illustrated in Figure 1. Previously identified tasks and challenges in two development settings were extracted from literature; product development and development of product prototypes with novel, advanced technology components. Data analysis of 138 monthly reports from an industry project was used to identify the tasks and challenges for four teams working with development of prototypes combining principles of an existing product and a novel technology.


*Figure 1. The research approach.*

The monthly reports were used as part of the project reporting between the team managers and the overall project manager. The monthly reports covered the project from the time of initiation and three years into the project (august 2011 - October 2014). The reports specifically listed task progression and challenges for the respective months. The reports were analysed using thematic analysis (Braun and Clarke, 2006) with two coding cycles: one for initial summarization of data, and one for thematising. The task and challenge entries, as well as a list of theme definitions were given unique identifiers: PP-#, CH-#, and Co-#, respectively. A data handling record was used to document all steps. To increase reliability of the data coding, team coding was used; a second reviewer was assigned to review the entries in the first coding cycle (Miles et al., 2014). After this, code definitions were compared to create a unified coding scheme. Coding themes originated mainly from literature, but with inclusion of themes emerging from the analysed data as well. To discuss the findings, observations and meeting notes from the project period were used.

## 3 RELATED WORK

In this paper, two main terms are investigated, tasks and challenges. Tasks are understood as work underdone by engineers in a company, following work processes and procedures. Challenges are understood as areas that are identified to cause an additional effort to solve. This section will focus on tasks and challenges in two contexts; product development, and the development of prototypes with novel, advanced technologies. A distinction is made between regular product development, focused on the optimization of functionality and properties desired by a customer in a smart way (Mortensen, 2012), and early development of devices (prototypes) with novel technological principles applied more focused on exploring the benefits of the novel technology for possible exploitation (Iansiti, 1995; Nobelius, 2002).

### 3.1 Tasks and challenges in product development

Within the area of product development both tasks and challenges have been subjects of investigation as these are encountered every day in companies A general agreement on six general phases of design can be found: establishing a need, analysis of tasks, conceptual design, embodiment design, detailed design, and implementation (Howard et al., 2008). Each of the phases are often divided into smaller, well-defined tasks to enable concurrent work (Andreasen and Hein, 1987). Other tasks often found are documentation and specification as part of quality measures for the company, as well as what is produced (Pahl and Beitz, 2007).

In general, challenges for product development are represented by performance, schedule and cost (Mankins, 2009). When examining product development literature, subjects such as interfaces (Tomiyama et al., 2007), functions, properties, and structure are prominent (Pahl and Beitz, 2007; Ulrich, 1995). A literature study of previously reported challenges in mechatronic development indicated challenges within product, activity, mind-set, competence, organizational aspects, and other aspects (Morkeberg Torry-Smith, 2013). This indicates that challenges are found in multiple dimensions, and not only specifically target the product, but are also related to process and organization. Therefore, specific challenges will be extracted in the following section.

All together, the list of tasks and challenges in product development is inexhaustible, as each engineering domain will have each its tasks to undergo and challenges to solve. The following section will be used to draw out some of the expectations for what themes will be prominent.

### 3.2 Applying sub-systems based on novel technology

As complex products are not easy to decompose in order to allow new technology components to fit, a re-design may be needed. One approach is to scale down to prototypes, to a focused level where the combined system can be assessed (Ulrich and Eppinger, 2008). Uncertainty is often mentioned together with technology development (Rogers, 1995; Cooper, 2006; Mankins, 2009). The introduction of the technology element to the product system will result in challenges on more than one level. The general assumption in such a setup is that due to the already existing product design, some things may already be partly pre-defined, such as structure and properties. Therefore, it may be expected that the first general development phases will instead be focused on selecting and defining a match in a proper concept (Iansiti, 1995) as well as familiarization of the technology to break the habits connected with the replaced technology (Katz and Allen, 1985). For familiarization, the transfer of technology prerequisites an interaction between product development and technology development company as "People, not papers, transfer technology" (Foley, 1996). Understanding the technical issues of a technology before transferring it is found to be a challenge (Cohen et al., 1979).In the implementation phase, an emphasis can be expected on testing the prototype as functionality and desired properties need to be verified (Ullman, 2009). As two or more inter- or intra-organizational units are to interact, an agreement on resources, responsibility, differences in aims and ownership have been among the challenges reported by researchers focusing on supporting the process (Nobelius, 2002; Stock and Tatikonda, 2008; Larsson et al., 2006) Thus, project management can be expected to be a prominent factor (Iansiti, 1995).

### 3.3 Summary

The main tasks and challenges found in literature will serve as a guide for the analysis. Some of the tasks and challenges are expected to be increased when combining existing products and novel

technology in prototypes. Literature indicates that the occurrence of testing tasks should be expected to be high. Also, implementation and project management tasks are expected to be more frequent when integrating novel technology. As a separate task before or during the development process, familiarization should be a substantial part of the work with integrating the technology sub-system.
The technical development of the product is indicated to be a challenge due to the input of a novel technology.

## 4 INDUSTRIAL CONTEXT

A Danish 10 M€ project investigating, developing, and applying the Electro-Active Polymer (EAP) technology for transducer applications, has been used as a case for this paper. The project was divided into ten work packages (WPs). The WPs focused on the production as well as the product side of the technology (Sarban, 2013). The project was structured as a public-private partnership (PPP) project with multiple partners from industry and academia (I1-4, A1-3) (Hansen, 2013). Focus in this paper is on four WPs (denoted project 1-4) developing prototypes with the technology. For an overview of the projects, see Table 1.

*Table 1. Overview of projects*

| | Project 1 | Project 2 | Project 3 | Project 4 |
|---|---|---|---|---|
| Application | Incremental motor principle | Energy harvesting device | Heating control valve | Loudspeaker |
| EAP tranducers used | 3 | 1-4 | 1 | 2-4 |
| Project partners | I1, A1 | I1, I2, A2, A3 | I1, I3, A1 | I1, I4, A1, A3 |
| Prototype iterations | 2 | 3 | 3 | 3 |

In each of the projects, three sequential prototypes were planned. The data analysed were from the two first prototype iterations. The main difference between the projects was that in project 1, a principle, rather than a specific product was investigated. This meant that the prototype less comprehensive, compared to the other three projects. Project 1 was also initiated later than the other projects.
The project setups, following the PPP structure, had a virtual organization structure, here denoted the PPP shared setup.

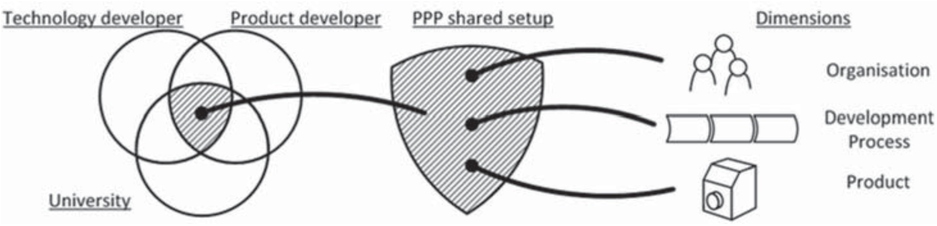


*Figure 2. Project setup*

The shared setup resources from each of the organizations were shared in a process to produce prototypes for demonstration and evaluation purposes, as illustrated in Figure 2.

## 5 FINDINGS

A total of 766 entries, from the 138 monthly reports were distributed as presented in Table 2.

*Table 2. Overview of reports and distribution of entries in the four projects*

| Project | Project 1 | Project 2 | Project 3 | Project 4 | Total |
|---|---|---|---|---|---|
| # of monthly reports | 30 | 39 | 31 | 38 | 138 |
| # of task entries | 68 | 257 | 117 | 98 | 540 |
| # of challenge entries | 30 | 100 | 58 | 38 | 226 |
| Sum of entries | 98 | 357 | 175 | 136 | 766 |

The entries were distributed with respect to tasks and challenges. The graphs are displayed with respect to the projects and the dimensions illustrated in Figure 2.

### 5.1 Tasks

All of the 540 task entries (100%) were used in the thematic analysis. As some entries represented multiple tasks a total of 683 task entries were identified. An abstraction adjustment of these, together with classification and collection resulted in 17 main themes. The themes were presented in Table 3 along with percent of total themes and theme description. The descriptions give an insight to the lower level themes found in coding cycle 1.

*Table 3. Themes, percent and theme description for tasks.*

| Themes (Abbreviation) | % | Theme description |
|---|---|---|
| Test (TEST) | 14,1 | Test of systems or sub-systems developed within the projects. |
| Detailed design (DET-DES) | 13,5 | Detailed design activities. |
| Implementation (IMPL) | 13,0 | Constructing and installing the system or sub-systems |
| Project Management (PROJ-MAN) | 11,4 | Project definition, scoping, agreements, planning, and resource allocation activities, |
| Analysis (ANA) | 8,3 | Simulations, calculations and other tasks involving an analysis of system or sub-system performance |
| Conceptual design (CON-DES) | 8,2 | Concept design, brainstorms. |
| Problem (PROB) | 7,5 | Problems, failures, and repair activities |
| Documentation (DOC) | 5,7 | Documentation of system, test, or project progress. |
| Academic work (ACA-WOR) | 4,0 | Entries directly related to academic work, such as publishing and conferences, as well as preparations for these. |
| Specification (SPEC) | 3,1 | Specification of systems or sub-systems, current or future |
| Collaboration (COL) | 2,9 | Entries explicitly communicating sharing of knowledge and / or resources across project organisations |
| Procurement (PROC) | 2,3 | Finding, ordering, and purchasing parts or components from third parties. |
| Delay (DEL) | 2,2 | Delays in project due to various causes. |
| Review (REV) | 2,0 | Review of system or development activities. |
| Embodiment design (EMB-DES) | 0,9 | Embodiment design activities. |
| Limited Resources (LIM-RES) | 0,7 | Explicit entries on limited resources or limited progress due to limited resources |
| Familiarization (FAM) | 0,1 | Explicit familiarisation of project members with the technology and / or project. |

According to Table 2, which lists the themes along with their proportional occurrence (across the four projects in total), themes relating to the building and testing of the prototypes are prominent for the projects It is also seen that many of the identified tasks from literature are represented.
Figure 3 shows the distribution of themes for each individual project to enable an analysis of common factors.
It was expected that TEST should be high, as well as PROJ-MAN. Common for the four projects was that they all had a representation of TEST as a prominent task e.g. among the top four for each project. It can also be seen that tasks related to constructing and installing (IMPL) is prominent in all four projects. This is an indication of the technology input to be affecting the development process.
In that relation the familiarization task (FAM) was also expected to be high. However, it occurs only once in a single project.

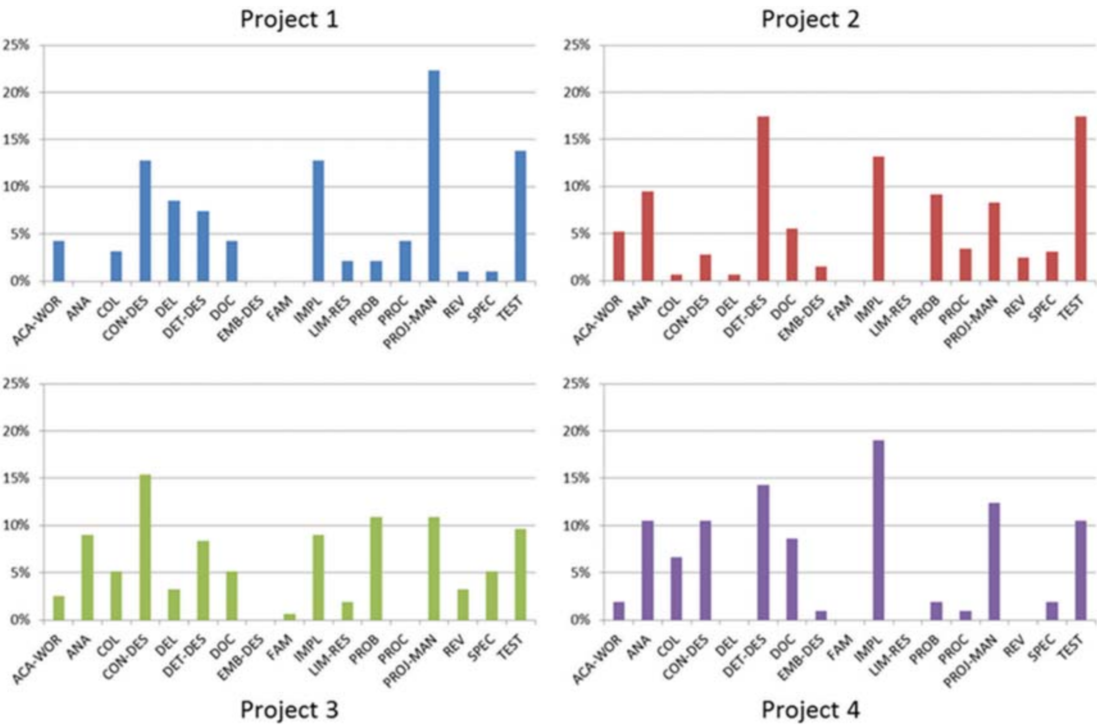


*Figure 3. Tasks distributed on projects in percent*

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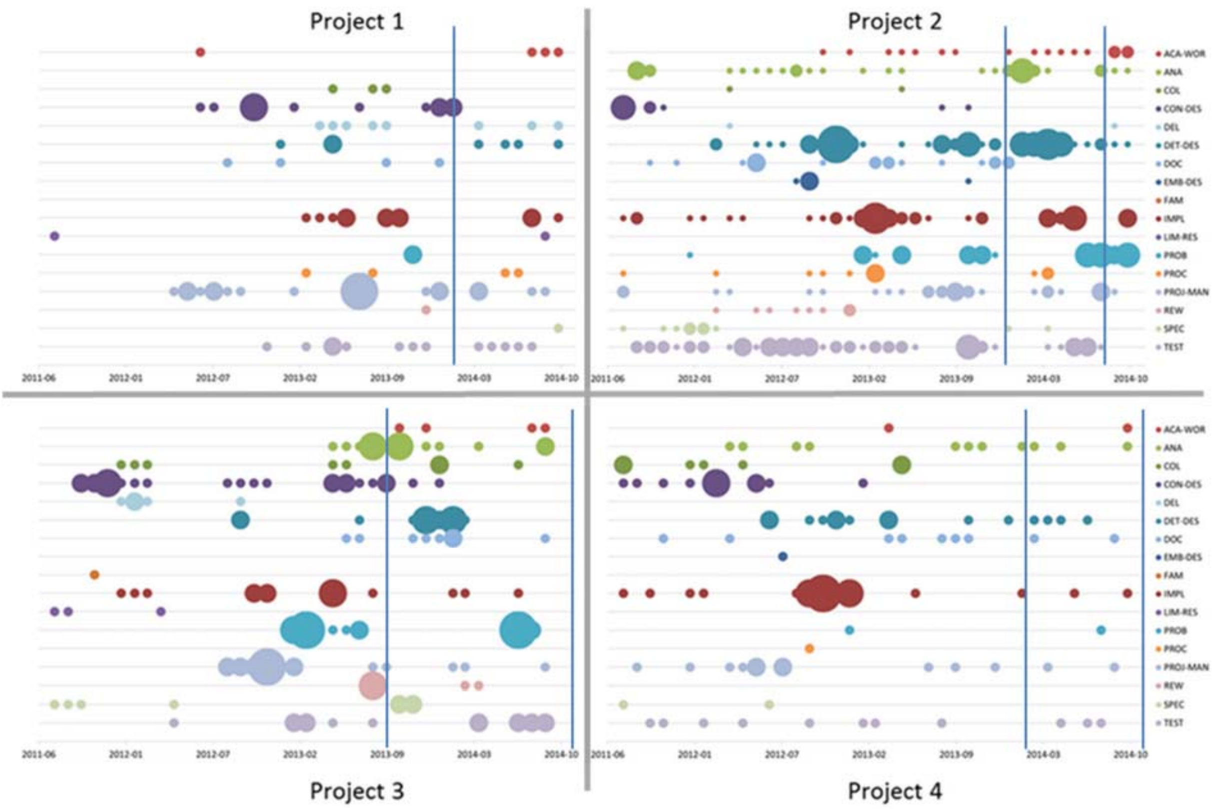


*Figure 4. Task entries in the projects over time. Dot size indicates relative number of entries for each theme. Vertical lines indicate prototype completion milestones.*

Figure 4 illustrates how the task entries were distributed over time in each project. Here, the number of entries related to a specific theme is correlated to the size of the dots. The larger the dot size, the more entries within the theme in that particular month. Project 1 was initiated later than the other projects, which can be seen from the lack of entries in the beginning of the figure.

As seen in Figure 4, most activities are distributed throughout the period in a greater extent than would be expected in product development projects with more mature technologies. Conceptual design (CON-DES) does occur most frequently at the early stages, but still occurs in all projects after detailed design (DET-DES) activities have been performed. Test (TEST) and implementation (IMPL) entries are seen regularly in most of the projects (see Figure 4), but Project 2 stands out with a high number of entries from an early stage. Problem (PROB) entries seem to occur close to test and implementation activities, which would also be expected in mature product development.

## 5.2 Challenges

Out of the 226 challenge entries, 202 (89.4%) of these indicated challenges in the four projects. Some of these entries represented multiple challenges, resulting in 251 challenges entries identified in total. Following the same procedure as with the tasks, nine main coding themes were identified. These are presented in Table 4.

*Table 4. Themes, percent and theme description for challenges.*

| Code (abbreviation) | % | Code description |
|---|---|---|
| System development (SYS-DEV) | 31,9 | Challenges related to system development, including analysis, procurement, requirements, construction and testing the systems and sub-systems. |
| Limited resources (LIM-RES) | 20,7 | Limitations in personnel, equipment, financial or production capabilities, as well as time for activities. |
| Project planning (PRO-PLA) | 14,7 | Challenges related to planning of activities to ensure timely completion of project. |
| Resource allocation (RES-ALL) | 11,6 | Allocation of human, physical, or financial resources, including new positions within the project. |
| Robustness (ROB) | 9,6 | Issues with robustness of system or sub-systems, e.g. stability, failures, lifetime, and repairs. |
| Technology component production (TEC-PRO) | 7,6 | Production quality and production capability challenges. |
| Organizational support (ORG-SUP) | 1,6 | Limited support for the project within an organisation. |
| Technology development (TEC-DEV) | 1,2 | Challenges due to technology performance, e.g. core material composition and component performance. |
| Technology familiarization (TEC-FAM) | 1,2 | Resource use for familiarization with the technology. |

Cost is not directly represented in Table 4 but can be seen through the theme LIM-RES. Again, these numbers are for the projects combined, and not for the individual projects. Figure 5 shows the proportional distribution of challenges for each of the four projects. The challenges identified can be organized after focus: Organisation, System and Technology. The organisational challenges cannot be said to be directly linked to development with novel technology. They may be a result of the collaborative setup presented in Figure 2. Therefore, a delimitation is made here; focus will be on system and technology, i.e. the five challenges indicated in Figure 5: ROB, SYS-DEV, TEC-DEV, TEC-FAM, and TEC-PRO. It can be seen that the projects 2-4 have a high occurrence of SYS-DEV. Project 1 on the other hand does not have any entries in the SYS-DEV theme.

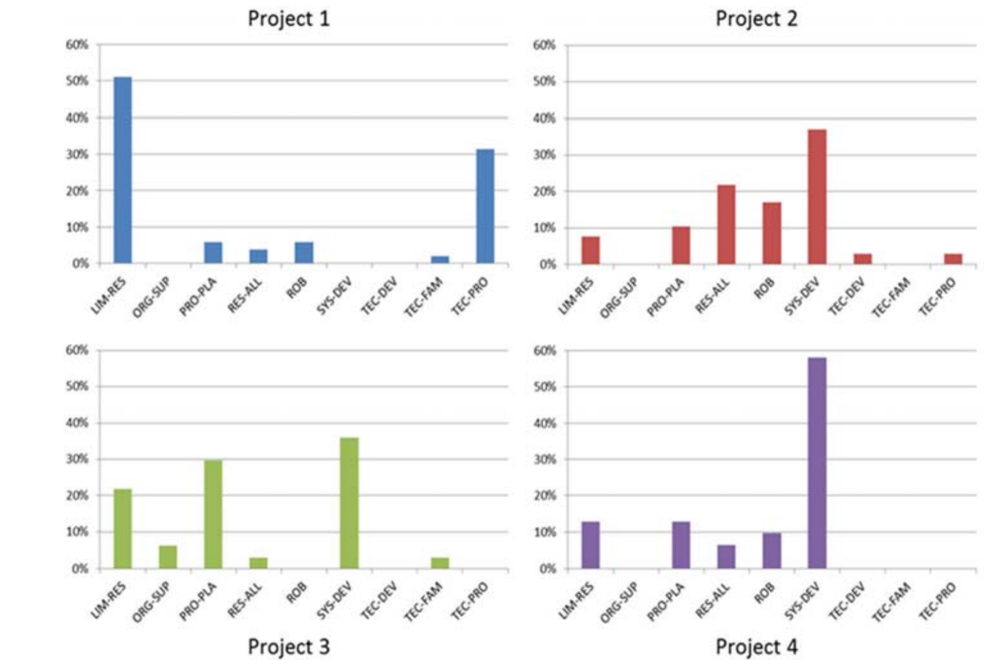


*Figure 5. Challenges divided on projects in percent*

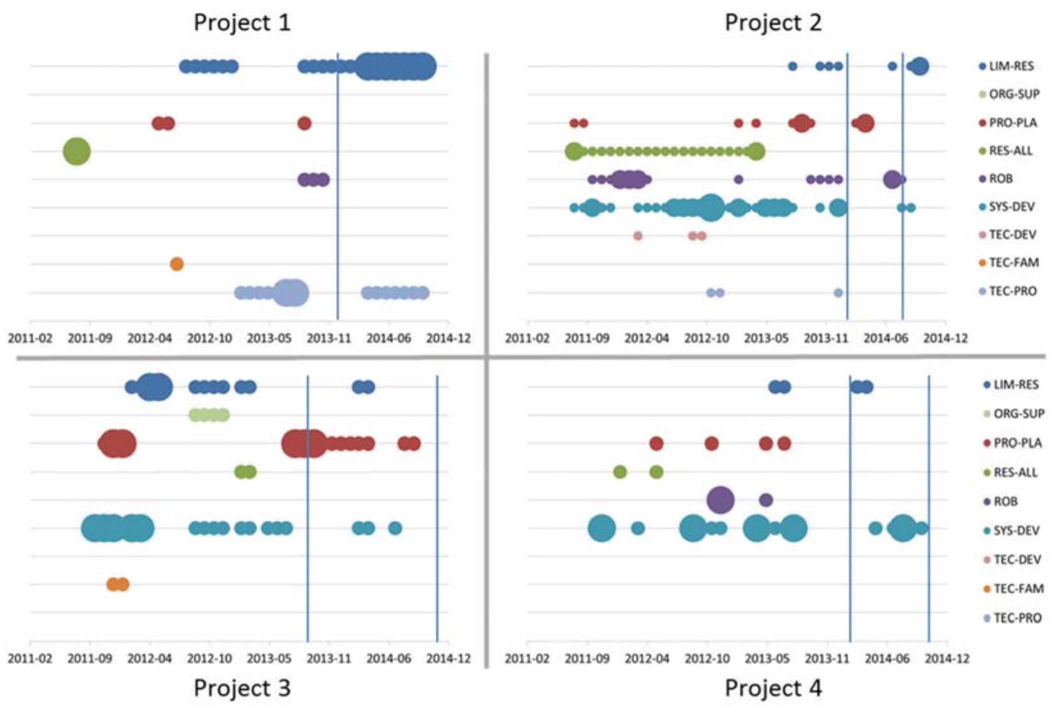


*Figure 6. Challenges in the projects over time. Size of dots indicates relative number of entries within each theme. Vertical lines indicate prototype completion milestones.*

While challenges are distributed throughout the period for all projects, as seen in Figure 6, there is little that obviously distinguishes the challenge distribution in the case projects from that which could be expected in more mature development projects. System development (SYS-DEV) challenges are present throughout almost the whole period for projects 2-4, but system development challenges can also be expected to occur, at least in some form, over most of the project period in mature product development. Technology component production (TEC-PRO) challenges are seen for a considerable amount of time in project 1, but production challenges can also hinder more mature product development.

## 6 DISCUSSION

Two main points will be discussed: the findings and study limitations.

### 6.1 The findings

The analysis revealed 17 task themes and 9 challenges themes. While a few prominent observations could be done regarding test, implementation, project management, and familiarization for the task themes, for challenge themes, only the system development challenge theme showed a clear similarity between the four projects. The rest of the identified themes either do not showing a tendency or as in the case with the challenges, cannot be directly linked to the development with novel technology.

That familiarization, expected to occur frequently in this setting, has not been found as a task theme reported on may be an indicator that it was either not done, or that it was not reported as a specific task.

It was expected that the SYS-DEV challenge would be high for the projects, but the big difference between projects 2-4 and project 1 was not expected. The main difference in the projects, as presented in the Industrial context section, was the application area, which may be the cause. Projects 2-4 were directly linked to industrial companies, whereas project 1 was used to explore an incremental motor principle - a considerably simpler system than those in the other projects.

To further investigate the correlation between the tasks noted by the project managers in the monthly reports and the time spent on the tasks a comparison with Gantt charts could be used. Looking at the distribution of entries shown in Figure 4 is can be seen that multiple entries can be made for a single month and it could also be seen that most of the themes were distributed over a longer period of time, compared to regular product development. Figure 6 however, revealed little to distinguish between the challenges in this context and a more mature product development.

In the industrial project, a prototyping with technology of low maturity level was tested. A comparison with a more mature technology would be interesting to map the differences between low maturity level and high maturity level, to find clear indications of the effect on the different themes.

### 6.2 Study limitations

Team coding (Miles et al., 2014), i.e. an additional researcher was used to analyse the data. This was done in order to strengthen the reliability of the analysis. In order to have better inter-coder reliability, the code definitions were discussed and decided upon for the second coding cycle. On the matter of intra-coder reliability the data has been aimed to be coded in focused, single sessions. A re-coding might have given higher intra-coder reliability (Miles et al., 2014). However, the data has not been re-coded for this paper.

Only one source of data has been analysed in this paper. In general, it may be discussed whether the data is a one-to-one representation of the tasks and challenges in the projects as only the comprehension of the team managers is represented through the monthly reports. The tasks and challenges noted in the monthly reports were filtered by the team managers' perspectives. Therefore, the dataset analysed is a representation of what the team managers normally report in their own organisation, and what they put emphasis on in that particular situation. Additionally, some tasks and challenges may have been met within the projects without being included. This means for the results, that they should be regarded as preliminary. For an extended study, additional sources of data should be combined for triangulation of findings. This would strengthen the validity of the findings.

## 7 CONCLUSION AND FURTHER WORK

In this paper empirical data of the tasks and challenges connected to development projects implementing novel technology has been extracted from 138 monthly reports from an industrial project over a three year timespan. A thematic analysis was performed to identify themes within the dataset.

Through the analysis of the data 17 task themes and 9 challenge themes were identified. When analysing the themes for each of the projects a number of similarities were seen. It was found the task themes test, implementation, and project management tasks had a high occurrence, which was expected. Based on literature it was expected to find technology familiarization tasks, however, only a single entry was found for the theme. For the challenges, a high occurrence of system development challenge was found which could indicate an effect from testing novel technology with low maturity level in product context at an early stage.

It was found that the predominant tasks and challenges are distributed over long periods of time, rather than in chunks linked to a specific development phase.

Further research could include utilization of additional sources of information. This would strengthen the analysis of a project of this type. Also, a more detailed analysis of the entries could provide valuable insight into the tasks and challenges encountered.

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## ACKNOWLEDGMENTS


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# 10.2 PAPER B: A MULTI-LAYERED APPROACH TO ARCHITECTURE MODELING – APPLIED TO TECHNOLOGY PROTOTYPES


Published in Journal of Concurrent Engineering: Research and Application, July 2015

Authors: Ravn, P.M., Guðlaugsson, T.V., Mortensen, N.H.

**Abstract**

Companies that wish to include novel technology in the product portfolio may need to test and evaluate the technology with the use of prototypes to learn its benefits. Without clear knowledge of the benefits of the technology to the products in the portfolio, in the form of increased performance, added functions or material savings, the prototype development can be hard to manage. In this paper two contributions are made. The first adds to the vocabulary of prototyping, defining technology prototype, a prototype used for testing a novel technology in the context of an existing product. The second is a tool to model and manage technology prototypes: the Technology Prototype Product Architecture Tool (TePPAT). The TePPAT is a product architecture tool with three main sections: Purpose, Concept, and Architecture.

The TePPAT was tested in four industry cases, all part of a public-private partnership project to support the development of technology prototypes using Electro-Active Polymer transducer technology.

The findings showed that the TePPAT supported the development teams in the four cases. It is concluded that the TePPAT can support multidisciplinary development teams in modeling and managing technology prototypes and can be correlated with improvements in the team collaboration, communication, and development performance.

*Standard Article*

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# A multi-layered approach to product architecture modeling: Applied to technology prototypes

**Poul Martin Ravn, Tómas Vignir Gudlaugsson and Niels Henrik Mortensen**

**Abstract**
Companies that wish to include novel technology in the product portfolio may need to test and evaluate the technology with the use of prototypes to learn its benefits. Without clear knowledge of the benefits of the technology to the products in the portfolio, in the form of increased performance, added functions, or material savings, the prototype development can be hard to manage. In this article, two contributions are made. The first adds to the vocabulary of prototyping, defining technology prototype, a prototype used for testing a novel technology in the context of an existing product. The second is a tool to model and manage technology prototypes: the Technology Prototype Product Architecture Tool (TePPAT). The TePPAT is a product architecture tool with three main sections: Purpose, Concept, and Architecture. The TePPAT was tested in four industry cases, all part of a public–private partnership project to support the development of technology prototypes using electro-active polymer transducer technology. The findings showed that the TePPAT supported the development teams in the four cases. It is concluded that the TePPAT can support multidisciplinary development teams in modeling and managing technology prototypes and can be correlated with improvements in the team collaboration, communication, and development performance.

**Keywords**
product architecture, architecture modeling, technology integration, technology prototypes, prototype development

## Introduction

Developing new product capabilities will inevitably introduce challenges in achieving performance, schedule, and budget goals (Mankins, 2009). Technology development, regarded as more explorative than product development (Nobelius, 2002), can face bigger challenges in these three dimensions, as unknown aspects of an unexplored technology span multiple dimensions. From a product development point of view, the result of new technology development often means either completely new sub-systems or significantly changed sub-systems in the product, and both the technology developers and the recipients of the technology development face a number of uncertainties in integrating the technology into products. It has been shown that when developing systems incorporating novel technology, changes are not limited to single elements, but a multitude of other design elements that together make up the system (Henderson and Clark, 1990). Other studies have indicated that applying a system-focused approach, rather than an element-focused approach, supports aims of optimal performance (Tanner et al., 1989), higher development speed, and higher research and development (R&D) productivity (Iansiti, 1995). Some of these studies point in the direction of using product architecture modeling to overcome the increase of uncertainty in technology development projects.

Product architectures have a strong link to how companies design and manufacture products, for example, through development management, product change, or product performance, especially in R&D (Ulrich, 1995).

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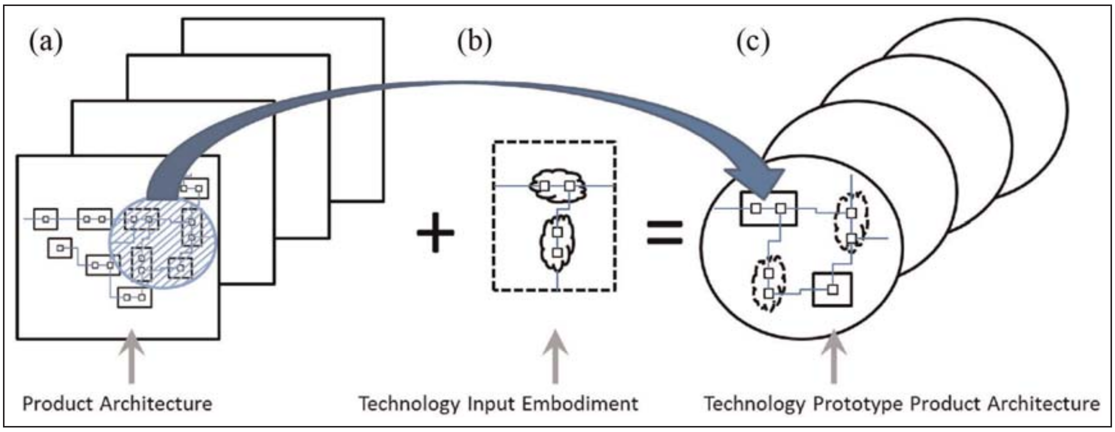


**Figure 1.** The pairing of (a) existing product or concept principles and (b) technology input into (c) technology prototypes. The technology prototype product architecture is a kind of product architecture. The focus in this article is on the technology prototypes and their product architectures.

This means that product architecture modeling may be a useful way to overcome the challenges of meeting performance, schedule, and budget goals. However, the predominant product architecture modeling approaches are mainly used in a more mature technology environment with a product as the end result. A focus on the use of product architecture modeling in a technology development environment where the end result for a project may be a technology prototype, rather than a product, has been lacking. In a technology development environment, the focus on the development of the technology itself leads to advancement in regard to function, properties, or performance in various dimensions, thus posing challenges to the development of such prototypes.

A technology development and evaluation project that was initiated in 2011 has targeted the commercialization of the novel electro-active polymer (EAP) transducer technology in a public–private partnership (PPP) (Hansen, 2013) project. One of many efforts toward commercialization was to develop a number of technology prototypes based on existing products estimated to be able to exploit the technology. The end product was envisioned as EAP transducers as a product sub-system, providing functionality and features to a product. The technology prototypes were built to demonstrate the integration and application of EAP transducers in different use and performance areas.

This article focuses on the modeling of product architectures in the development process of technology prototypes, demonstrating the use of a novel technology in an existing product or product concept. Using product architecture modeling makes it possible to analyze the product elements, their relations, and derived functions, in the technology prototypes. This article investigates the type of information that should be captured, and a modeling tool, the Technology Prototype Product Architecture Tool (TePPAT), is introduced. The TePPAT is used to collect and represent different types of information to describe the product architecture in multiple layers. The modeling addresses technology prototypes based on a combination of existing products and input from an emerging technology, as shown in Figure 1.

First, an introduction to the terms *product architecture* and *technology prototype* is provided, followed by a review of related work within product architecture modeling and the requirements for a modeling tool. Then, a description of the methodology is presented, followed by a description of the TePPAT modeling tool. The TePPAT was used in four industry projects and the findings from these are presented. Finally, the applicability of the modeling approach and the validity of the findings are discussed, and conclusions are drawn.

## Product architectures and evaluation of emerging technology in products

As a result of many different understandings and definitions of *product architecture* and *prototypes*, the two will be defined here for clarification.

### *Product architecture*

In system theories within the technical domain, products can be described through product structures. These are described as the sum of elements and their relation to each other, with a system boundary (Hubka and Eder, 1988). Based on a specific product structure, a product can deliver effects, both desired, for example, a holding effect, and undesired, for example, a noise effect. Andreasen et al. (1996) described a product as composed of multiple, superimposed, functional structure views from four basic classes: genetic, functional, product life, and product assortment. Functional structures are seen as the basis for product architectures, a term defined differently by different authors. Eppinger and Browning (2012) defined product architecture as a product structure that gives rise to a product's function and behavior. Ulrich (1995) defined product architecture as a scheme of how functions are allocated to physical components resulting in functional elements with relations, for a single product. Harlou (2006) defined architecture as a structure of a system constituted by standard designs and/or design units at three levels: product assortment, product family, and product. Design units may be functions, organs, parts, or an encapsulation of a group of these (Mortensen and Andreasen, 1996). Kvist (2010) stated that regardless of the perception of the term product architecture, these have to do with decomposition, arrangement, and interfaces. Standards, such as the ISO 42010 (Institute of Electrical and Electronics Engineers (IEEE), 2011), add an architecture viewpoint, framing a stakeholder's concern, such as purpose. Alvarez Cabrera et al. (2011) presented three goals of a product architecture model that enhance efficiency in the design of a product: provide overview, support integration, and provide traceability. Product architecture in this article combines the definition of Harlou and the goals from Cabrera: a structure of standard designs/design units that enhance efficiency in the design of a product by providing overview, supporting integration, and providing traceability.

## Prototyping with novel technology input

There are two main understandings of the word prototype found in product development literature. The purpose of both is to gain insight into the intended functions and properties of the object being constructed, but in different phases of a product design. The first covers the whole range of design models used to gain insight into the functions and properties of the product being designed, (e.g. Ullman, 2009; Ulrich and Eppinger, 2008). The second is used to describe a specific type of design model used for instance to evaluate usage, function, reliability, and marketing properties, before a pre-production series (Buur and Andreasen, 1989). In this article, the former understanding of the word is used.

Prototypes can be used to investigate uncertainties regarding particular functions, properties, and performance, for example, of new solution principles or the introduction of technological abilities into a product. Traditional methods of manufacturing are often used in prototyping, but simulation and rapid prototyping, such as multiphysics simulation and three-dimensional (3D) printing, are also utilized. Prototypes can be broadly classified as physical or analytical (Ulrich and Eppinger, 2008). Physical prototypes are typically used to detect behavioral phenomena through real-world tests. Analytical prototypes, such as multiphysics simulations, allow for rapid exploration or prediction of the influence of various parameters. Although used for different purposes, the two types complement each other in development: analytical prototypes to predict results of physical tests and physical prototypes to verify results of simulations. Additionally, a classification of the degree to which the prototypes implement the functions of a product, focused or comprehensive, can be used (Ulrich and Eppinger, 2008). The focused prototype implements few or some functions, whereas the comprehensive includes an amount of functions closer to those of the actual product.

Artificial systems, such as products, serve a user's purpose (Hubka and Eder, 1988) and the use of prototypes in technical development is also driven by the engineer's purposes. These purposes can be learning, communication, integration, and milestones (Ulrich and Eppinger, 2008). According to Houde and Hill (1997), communicating the specific purpose of a prototype is essential as the prototypes themselves do not necessarily communicate their purpose to observers.

Ullman (2009) distinguished between four different types of prototypes: proof-of-concept, proof-of-product, proof-of-process, and proof-of-production. An alpha, beta, pre-production, and experimental or engineering prototype categorization links the prototype to the development process (Ulrich and Eppinger, 2008). These types and categorizations are very broad, which is why a more specific definition will be used in this article.

Prototypes developed to investigate and demonstrate the performance of a novel technology are, in this article, referred to as *technology prototypes*. These are a kind of experimental prototypes that demonstrate the principle of the use of a novel technology in part of an existing product. Technology is, in this article, regarded as the knowledge of scientific principles and the ability to apply these to produce an output from a technical system. In technology prototypes, it will often not be beneficial to implement all functions of the finished product, but rather to focus on implementing core functions, to which the novel technology provides a plausible solution to develop and test. The technology prototypes can be physical or analytical depending on the need. Technology prototype product architecture will in this case either consist of (a) part of an existing product architecture and an instance of the technology system (e.g. a prototype of a loudspeaker building on known product architecture, but with additions or changes hereto) or (b) a completely new architecture within that product field, made possible by the new technology (e.g. a prototype of a loudspeaker exploring new principles). This is referred to as radical innovation (Smith, 2010). The technology prototype product architecture is an instance of a product architecture (see Figure 1).

### *Summarizing product architecture and prototyping*

Literature on product architecture and prototyping highlights some fundamental issues of importance for the situation being investigated in this article, that is, the testing and evaluation of novel technology to realize functions in a product. *Purpose* is of importance for both product architecture and prototypes as the purpose is the driver for building the technology prototypes. *Decomposition and composition* are of relevance as clearly defining the composition of a technology prototype can facilitate a clear indication of *where*, in the combination of existing product and novel technology, changes will be made to the design of the existing product. The *comprehensiveness* of the prototype affects the definition of the system boundary; communicating the comprehensiveness can aid in the definition of these boundaries and help maintain focus in developing the technology prototypes.

## Related work

In this section, related work within the subject of product architecture models is described and argued in relation to modeling of the technology prototype product architectures. The section is concluded with the aims for such a model.

### *Product architecture models*

Product architecture modeling is used to support product development in modern companies, and multiple approaches exist to model both individual product architectures and product family architectures. Product architecture models are based on a certain viewpoint of the product of interest (IEEE, 2011). These views may be visualized as diagrams, each describing the architecture in terms of a specific engineering discipline viewpoint, and therefore depicting the design solution from a specific perspective.

Function modeling is used to describe the desired functionality of a system (Pahl et al., 2007). A function structure is part of the analysis of the sub-functions and flow of, for example, material, data, and energy. Function modeling is a common approach in product development procedures to decompose a system into a functional hierarchy as a basis for targeting sub-solutions to sub-problems (Tjalve, 2003; Ulrich and Eppinger, 2008). Function heuristics are used for the definition of module-based product architectures (Otto and Wood, 1998; Stone et al., 1998). The Organ Diagram has been developed to depict functions and embodiment at an abstract level based on organs, that is, functional units seen as elements of a system (Andreasen et al., 2014). Organ diagrams are used for the definition of products, bridging function and structure (Ulrich, 1995). A Generic Organ Diagram (Harlou, 2006) has been developed to incorporate the depiction of product families together with the Product Family Master Plan (PFMP) (Harlou, 2006), illustrating generic design units of a product portfolio by using different views. The interface diagram (IFD) has targeted interfaces and the relation to product lifecycle management (PLM) systems (Bruun et al., 2014; Bruun and Mortensen, 2012), and the conceptual product platform (CPP) is used for the definition of a product platform early on in development projects (Gudlaugsson et al., 2014). The IFD distinguishes between a system view and a module view, which can be beneficial in the development of complex systems. Although the CPP is intended for use in early phases of development, it is focused on communicating the alternative variants of a product sub-component defined around a novel technology.

The design structure matrix (DSM) is a matrix approach used for modeling and identifying relationships between system entities (Steward, 1981). The DSM has been used to document architectures within product, organization, process, and multi-domains, and a combination of the former three (Browning, 2001; Eppinger and Browning, 2012). The DSM allows for control over and analysis of architectures through the study of interactions and interfaces among all of the elements in a system, and an analysis in graph theory, matrix mathematics, and specialized DSM analysis methods (Eppinger and Browning, 2012). The DSM3D has been used in module and variant creation (Alizon, 2007). Bonev et al. (2013) have combined the PFMP with DSM in the Product Requirements Development model to link and evaluate requirements.

Modular function deployment (MFD) (Erixon, 1998) is used to support the definition and evaluation of module concepts based on quality function deployment (QFD) analysis, thus aligning module proposals with customer requirements (Nilsson and Erixon, 1998). The alignment is supported through a Module Indication Matrix, in which module drivers and technical solutions are examined. The MFD facilitates reasoning about integration of multiple modules into one. While the MFD provides input for rational decisions on the modularization of a product, modules of the product are only represented in matrix form.

The A3 Overview is an approach that is used to collect, abstract, and present product architecture information in a way that can be understood and used by stakeholders (Bonnema et al., 2010). An A3 description of a system, composed of different view models, that is, a model-based description, a functional view, and a quantification of key parameters view, provides the information needed for developing an overview of the system (Borches, 2010). The A3 overview illustrates the principle of multiple view models to describe the product in a single overview to support communication, although an informal use guideline may result in overviews containing different models, dependent on the stakeholder. As models intended for other stakeholders should be finished in code understandable to those stakeholders (Buur and Andreasen, 1989), inconsistency may occur if or when the work is handed over to stakeholders using other types of models.

Common for most of these tools is that while they are purpose driven, they do not address the purpose of what should be built explicitly and few of them include working with modeling in different abstraction levels.

### Conclusion on related work

The description of related work in the preceding section has presented different approaches for modeling and structuring/synthesis of both single-product architectures and product family architectures. Most of these are applied to support product development. However, most of the models aim to support the development of an end product, that is, a product that is offered on the market. They are not aimed at overcoming uncertainties present in technology development projects. Furthermore, the models do not propagate the specific purpose of the technology prototypes to support a joint goal of the development team. The models mainly support (a) the modeling of system elements and their relations and (b) clustering of these elements into modules in order to optimize the design of the product or product program. The models used in the definition of modules, for example, DSM and MFD, focus on the modeling of relationships between elements within the product being developed. The models are used in product development under the assumption that the product is known, more or less completely. As the technology prototypes are likely to be developed concurrently with the technology itself, not all elements of the technology prototype may be known or some may change as the technology advances. What is therefore not found in the literature is how to support the development of technology prototypes and a description of their product architectures.

The previous section showed that *purpose, comprehensiveness*, and *decomposition and composition* should be drivers for such a model. An information model for depicting technology prototype product architectures elaborates on these points. To allow for focused development and to make it possible to pinpoint the specific parameters of the technology that must be improved, a model of a technology prototype product architecture should also enable identification of where in the technology prototype the novel technology is specifically located. This facilitates differentiating the technology elements in the technology prototype from other elements in the prototype. In this way, performance parameters and focus areas for technology development can be targeted.

## Methodology

The proposed model was developed and applied by means of iterations in a technology development project through an Action Research–based approach (Checkland and Holwell, 1998). The Case Studies were arranged as a multiple-case (holistic) design (Yin, 2009). An initial alpha version of the TePPAT was used to introduce the tool in four cases that were carried out in parallel, denoted Cases A–D. A total of 16 TePPATs were made in the cases. Feedback was used to revise and develop the tool and for improving and refining the results (see Figure 2). The sources of information were informal interviews, meeting notes from project participation, and participant observation. The latter two stem from active participation in the project work and the project meetings. The TePPAT has evolved through iterating between theoretical development of the tool and feedback suggestions, proposals, and experiences from meetings in the projects. It was expanded by revisions that afterwards were presented at meetings.

The cases were part of the same overall technology development and evaluation project, described in the "Introduction" section, with multiple collaboration partners from both industry and academia. The overall project was arranged as a virtual company (Chesbrough and Teece, 1996), sharing resources between the project partners. The development teams in the cases consisted of stakeholders from the collaboration partners: project managers, engineers, technology specialists, product specialists, professors, and PhD students. The team size of each project changed with the progress of the cases. The common denominator was the novel technology being applied in prototypes, but with a different product origin as a basis for

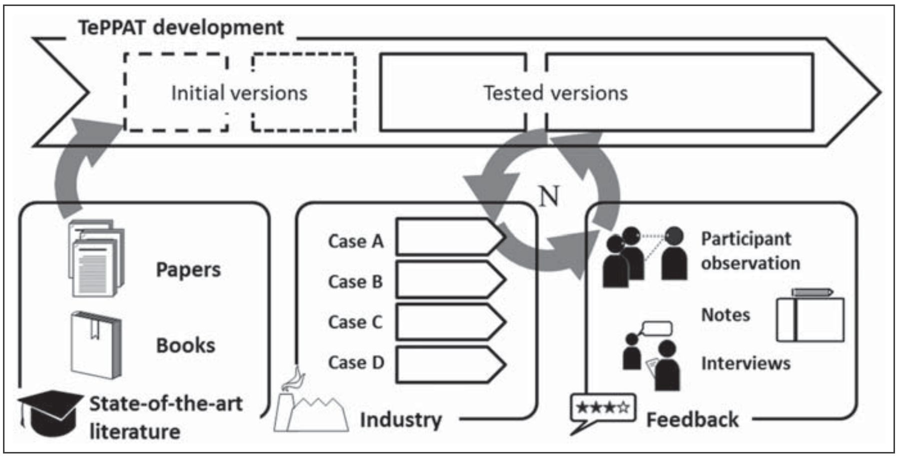


**Figure 2.** The development of the TePPAT. State-of-the-art literature formed the initial versions of the TePPAT. The TePPAT was tested iteratively (N) in four cases in industry and feedback was obtained through different means.

the cases. In the project, both large print-outs and electronic versions of the TePPAT were used.

## The technology prototype product architecture tool

The tool presented in this article is a visual product architecture modeling tool. The term visual is in this work understood to mean a simplified graphical representation of the object being modeled, to support the development.

### TePPAT model sections

The viewpoint of the model is to uncover the essence of the technology prototypes. This is described in three sections:

- The *Purpose* of the technology prototype, and quantified success criteria, specifying how the purpose will be achieved and quantifying the aims for the technology prototype.
- The *Concept* of the technology prototype is described by the main design units, as it is a composition of elements of the technology and part of an existing product principle.
- The *Architecture* of the technology prototype with elements and relations, and specific properties, capturing the system aspect by more than just the entities and relations. Specific information for the system, such as properties or other information linked to the prototype lifecycle, should be represented. Merely representing the structure will add little support to the development tasks.

The architecture section of the TePPAT is based on the Organ Diagram (Harlou, 2006) and has some commonalities with the IFD (Bruun et al., 2014). It is, however, targeted to meet the needs of the development teams within technology projects developing technology prototypes. The TePPAT is focused on the definition of a prototype's architecture and linked to information used in the development process, providing inputs to the refinement of the technology input. The TePPAT was developed and applied to support development of technology prototypes and capture information on the systems in which the technology is integrated and has not been tested in the development of commercial products. Utilization of the TePPAT in technology prototype development is intended to strengthen the development strategy and day-to-day work of a development team whose members belong to different domains and possibly different companies.

### The modeling formalism

The three main sections *Purpose, Concept*, and *Architecture*, as illustrated in Figure 3, provide a structured description of the technology prototype of interest. Reading from the top down, the TePPAT will provide information on the purpose and goals of the system from the Purpose section, through the Concept section where the decomposed concept with success criteria for each sub-system is described, to the Architecture section illustrating the system architecture. The term "success criteria" is used in this context instead of requirements due to the context of technology prototyping. Here, requirements are often not fixed, but rather used as a guideline, a goal to achieve,

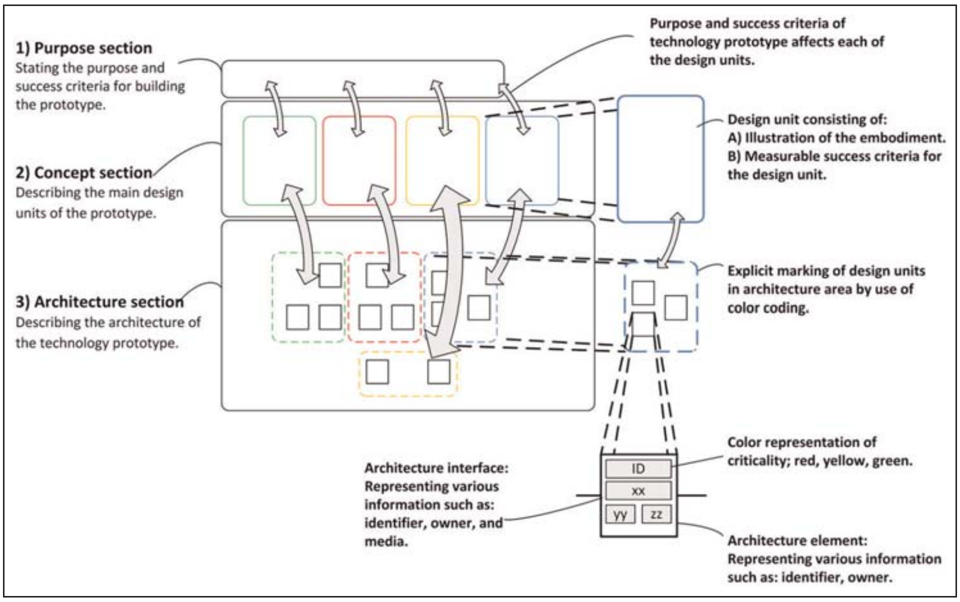


**Figure 3.** The three main sections of the TePPAT, (1)–(3), with the relations between them indicated by arrows.

or areas to be investigated, to learn about the technology prototypes. However, along with maturation of the technology, a transition to requirements may occur. The TePPAT is a tool intended to provide an overview of technology prototypes being developed—so the level of detail is on a system level and does not cover detailed design at the component level.

The *Purpose* section links the tool to the purpose of and reasoning behind developing the technology prototype. A definition of the purpose helps to delimit, or clarify, what the prototype should provide an insight into, based on the existing product or concept from which the prototype was derived. The purpose is based on knowledge of the existing product system, the solution principle that the novel technology shall replace, and the goals of and requirements for the prototype. Since the performance of the novel technology may not yet be equal to that of the solution principle it is to replace, the requirements are adjusted to realistic success criteria for the novel technology. It can be argued that if the purpose of the prototype cannot be stated, it should not be built.

The *Concept* section provides a description of the overall technology prototype concept and an abstracted decomposition of the technology prototype into subsystems: the design units. The rationale for such an abstraction is a definition of the main elements. This makes it possible to define success criteria for each of the main elements and to develop them concurrently. The decomposition in this section separates the technology element from the rest of the prototype. By separating the technology element, the development and learning points for each of the parts can be more easily targeted.

The *Architecture* section describes the product architecture of the technology prototype. The layout of the TePPAT should be based on a system perception of a technology prototype consisting of elements and their relations within a boundary defining what is "inside" and "outside" the product system (Hubka and Eder, 1988). The comprehensiveness of the technology prototype affects which elements are included and where the boundaries lie. The architecture is depicted through the use of functional elements and their relations. This provides a system overview. By reusing the decomposition made in the Concept section, in the Architecture section, sub-sections of the architecture are defined, and these provide a rational way of decomposing the technology prototype. The sub-system boundaries resulting from this decomposition are indicated by boxes with dashed lines to distinguish between interfaces to and from other sub-systems and interfaces within the subsystem. In situations where the sub-systems need to be modeled with increased detail, the sub-system boundaries will already be defined.

The functional elements contain additional information in fields, to encompass the need that stakeholders have of linking specific information to the system elements, for example, specific system properties. A criticality marking directs the focus on elements that need critical attention in the development or have not yet been developed. The lines drawn in the diagram

**Table 1.** Overview of Cases A–D.

| | Case A | Case B | Case C | Case D |
|---|---|---|---|---|
| Application | Generic incremental motor principle | Wave energy harvesting device | Heating control valve | Loudspeaker |
| EAP transducer task | Actuator | Generator | Actuator | Actuator |
| Aim | Bi-directional incremental movement by use of multiple EAP transducers | Energy generation by mechanical stretching of EAP transducers | Flow control by actuation of radiator valve pin | Sound wave creation by variable actuation |
| EAP transducers used in technology prototypes | 3 | 1–4 | 1 | 2–4 |
| Actuation frequency range (Hz) | Medium (5–100) | Low ( < 5) | Low ( < 5) | High (100–4000) |
| Average power (W) | Medium (1–50) | High (10–1000) | Low (1) | Medium (1–50) |
| Prototype iterations | 3 | 3 | 3 | 3 |
| Project partners | $I_1$, $A_1$ | $I_1$, $I_2$, $A_2$, $A_3$ | $I_1$, $I_3$, $A_1$ | $I_1$, $I_4$, $A_1$, $A_3$ |

EAP: electro-active polymer.

constitute the relation between the system elements. The interface can be one or more of the following types: material, energy, or information.

From a conceptualization viewpoint, the Concept section contains the two sides of a concept description (Hansen and Andreasen, 2002, 2003): the *idea with* and the *idea in*. The Purpose section describes the *idea with* on an abstracted level, while the Architecture section expands the details of the *idea in* the technology prototype. Thus, the relation between the Purpose section and the Concept section is a specification breakdown from the overall system-level purpose and success criteria to sub-system-level success criteria (Hansen, 1995). The relation between the Concept section and the Architecture section is the detail and concreteness. The relations between the sections are depicted as two-way in Figure 3. The rationale behind this is that discoveries made through test, simulation, or concept clarification may lead to insight into the technology prototype through *pop-up effect* or *pop-up incompatibility* (Hansen, 1995).

In the development of multiple subsequent technology prototypes, a time dimension is added to each instance of the technology architecture, dependent on the development strategy chosen. For a technology prototype, the relevant diagram can be used differently according to the chosen development strategy. If the strategy is to retain a specific technology prototype architecture design throughout the duration of the prototype iterations, scaling principles may be explored by projecting TePPATs for prototypes yet to be built. If different concepts are explored, the TePPAT can provide input to map the solution space of the technology architecture system through extraction of information such as system properties, system elements, and their relations.

## TePPAT industry example

An industry example of the TePPAT is now presented to illustrate how the model has been implemented and used.

### Case background

By aiming for commercial production of EAP transducers (Kiil and Benslimane, 2009), Danfoss PolyPower had set the goal of successfully introducing a novel technical alternative to linear electric motors to the market. Testing of the technology in different applications was underway in a large-scale PPP (Hansen, 2013), a development project with multiple industrial and academic partners (partners $I_{1–4}$ and $A_{1–3}$), supported by the Innovation Fund Denmark (IFDen). In this project, four sub-projects (Cases A–D) were working on integrating EAP transducers in multiple, very different technology prototypes. This resulted in different requirements as well as uncertainties for the EAP transducers in terms of geometry, interfaces, and functionality. For an overview of the cases, see Table 1.

### Applying the TePPAT

The TePPAT was developed and applied to support the development of technology prototypes, further develop a platform definition of the technology system, and to provide valuable input from an application of the EAP elements.

The TePPAT was developed due to a clear need for a tool that provided the development team with a clear, common overview from the prototype system purpose to sub-system requirements and product architecture design. As the project progressed, the TePPAT was

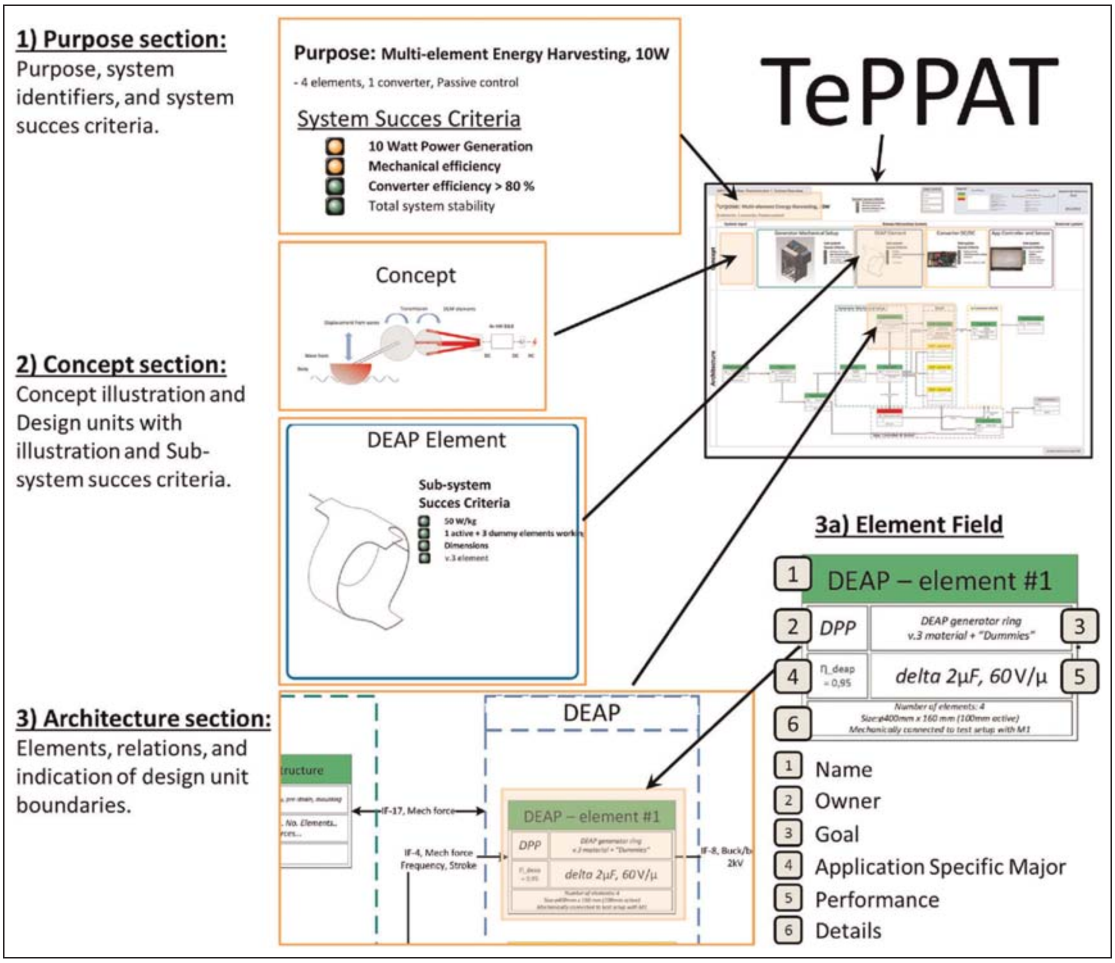


**Figure 4.** A TePPAT example from the IFDen project with highlights of the Main Sections (1)–(3).

continuously revised and refined to meet the needs of the project teams. Each of the prototypes had a corresponding TePPAT modeled in Microsoft® Visio®. The TePPAT representations were all within the same template, that is, the modeling formalism, but they allowed for the stakeholders to decide the content to a certain extent. A TePPAT example from Case B is shown in Figure 4.

### *The purpose description*

In the Purpose section, the purpose of the technology prototypes was stated, for example, "Multi-element Energy Harvesting," together with a number of key system features, for example, "4 elements, 1 converter, passive control" as seen in Figure 4 for Case B. Overall system success criteria were formulated in cooperation with the stakeholders. Color-coded fields were used to make it possible to track and evaluate fulfillment of the success criteria.

### *The concept description*

In the Concept section, the specific decomposition of the technology prototype into sub-system building blocks, or design units, was depicted along with illustrations for each of these. The illustrations were created by different means, for example, hand sketches, photos, and 3D computer-aided design (CAD) renderings, but with the same aim: to give a clear and logical breakdown of the system into its main building blocks. Specific success criteria for each of the different decomposition areas were stated along with indicators showing whether success criteria had been fulfilled, by use of color codes.

### *The architecture description*

The architecture of each of the technology prototypes was depicted in the corresponding TePPATs with functional elements and relations. The sum of these corresponded to the defined comprehensiveness of the technology prototype. Within each functional element, the following fields were defined:

*Name*—which provides an identifier of the element. The background color in the name field, indicating element completeness and/or criticality, was used to link the architecture to the development process, and to indicate what was inside and outside the system boundary.
*Owner*—the responsible project organization or person.
*Goal*—the desired result for the element.
*Performance*—how well the elements perform on a number of parameters.
*Application specific major*—an application-specific parameter of special interest, for example, the power efficiency of an element.
*Details*—data field with information specific to the element provided for specific stakeholders to see, which would be too specific or irrelevant for some stakeholders.

For the element relations, lines were denoted with numbers for identification, owner, and the type of relation. The effect flow of the element relations, often bi-directional, was indicated by arrows.

In an initial version of the TePPAT, the architecture elements in the Architecture section contained multiple data fields, for example, status of the development task. This particular field was found to be redundant, as task status was already controlled by Gantt charts. In one case, the team reported the need for linking a specific data parameter to the elements, an efficiency ratio ($\eta$), as this was a main concern in that particular case.

### Control of views

Based on a need in the project to communicate the technology prototype design in the development teams as well as upper management, the possibility of selecting specific views on the architecture was implemented. Control of visibility of views was made possible with coding of layers through Microsoft® Visual Basic® for Applications. The elements on the sheet were assigned to a specific layer: "Overview", "Detailed", or "Macro boxes." The "Overview" layer, by default always visible, contained all but the information in the *Details* field. The "Detailed" layer included the information in the *Details* field. "Macro boxes" were used to illustrate the specific decomposition of the system and were equivalent to the design units in the Concept section.

### Filling out the TePPATs

In general, the pattern of use of the TePPAT was often started by first filling out the purpose, through the concept, down to the architecture. In the progression of the projects, additional details of the TePPATs were added in an iterative manner, following the understanding obtained during the maturation of the technology prototypes. Details were added in the timespan from early concepts, building, testing, and reporting, to new prototype iterations. TePPATs were filled out in both physical and electronic formats. Electronic format was used in WebEx meetings to create on-the-fly changes. Printed versions were used to allow the many stakeholders to collaboratively work with and update the prototype description by noting comments and changes directly onto the posters, followed by an electronic update. Follow-up reviews with multiple stakeholders within each project were completed to ensure common understanding and agreement on the design.

In some projects, a more detailed view was needed to support discussions on sub-systems. Therefore, a design unit would be expanded into its own sub-TePPAT.

## Results from applying the TePPAT in the project cases

The results from applying the TePPAT in the cases are reported here with regard to the use of the TePPAT and the effects from using the TePPAT. The results are presented in Table 2.

The results were obtained from making a number of TePPATs to model physical and analytical technology prototypes in the cases. The TePPAT was used in a number of activities as a working document in both physical and electronic versions. Especially in the work with the definition of technology prototypes, a single page overview has been reported by stakeholders as an advantage of the TePPAT. The use of the TePPAT can be roughly divided into the following categories: reasoning why, defining the technology prototype, communication, and analyses. The effects from using the TePPAT ranged from better knowledge about the technology prototypes, aligning and strengthening the communication, to saving on technology prototype costs.

The observations of the teams using the TePPAT to plan ahead indicated that the teams needed clarification of details in consecutive technology prototypes. Using the TePPATs to supplement roadmaps and detailed design helped the stakeholders to define tasks and anticipate workload up front and to be able to carry these out in a concurrent manner.

Although the TePPAT modeling formalism was the same in Cases A–D, different ways of using the tool were observed in different cases. In Cases A–C, it was used on a regular basis during meetings, whereas in Case D, it was used less often. Despite being used less often in Case D, the team was observed to need the least guidance for using the TePPAT, or for using it to

**Table 2.** Usage and effects in the cases.

| Topic | Usage | Effect | Cases |
|---|---|---|---|
| Reasoning why | Defining a shared understanding of the technology prototype | Avoiding misunderstandings by aligning the modeling language between the stakeholders from different engineering domains | A, B, C, D |
| | Active usage of Purpose, Concept, and Architecture sections during meetings | Overview of the technology prototype designs<br>Agreement on shared description of technology prototype | A, B, C, D |
| Definition of the technology prototype | Defining purpose | Keeping the overview during development work<br>Keeping a steady course in the development for defining when the prototype was finished and what the level of success was | A, B, C, D |
| | Defining concept | Defining of the responsibilities on a general level between the teams and the main interfaces | A, B, C, D |
| | Defining architecture | Increasing common overview for the development team | A, B, C, D |
| | Defining development tasks | Supporting the project management | A, B, C, D |
| | Identification of interfaces, elements, and functions of the technology prototypes | Pin-pointing the key interfaces and functionalities from introducing the novel technology | A, B, C, D |
| | Agreeing on interfaces | Enabling resource savings<br>Avoiding confusion | A, B, C |
| | Abstracting detailed, technical discussions during meetings | Enabling different engineering domains to understand each other | A, B, C, D |
| | Defining system and sub-system tests | Enabling verification of system and sub-system tests | B, C |
| | Comparison of sub-system alternatives | Clarifying system composition | A |
| Communication | Communication of the technology prototype designs from an abstracted system level and down into details within each functional element | Strengthening communication and discussions internally in the teams by allowing pinpointing of discussion objects | A, B, C, D |
| | Communication to the upper management of the project regarding strategy planning and progression of the technology prototypes | Strengthening external communication of the technology prototypes by allowing an abstracted and coherent overview of the technology prototypes | A, B, C, D |
| Analyses | Iteratively modeling future instances of the technology prototypes ahead of building them in addition to roadmaps | Reducing the development cost of consecutive technology prototypes by indication of what elements could be reused<br>Increasing visibility of development strategy | A, B |
| | Performing gap analysis | Guiding discussions | B, C |
| | Live update from purpose to architecture in a single view | Increasing meeting efficiency by allowing on-the-fly changes during meeting | A, B, C, D |

communicate the technology prototype design to project partners.

In the cases, the TePPAT description became a living document in the sense that not only would detail increase over time as knowledge was gained on the development of the technology prototypes but the description would also change depending on the progress of the concurrent development of the core technology.

## Discussion

In this section, the results are discussed along with the use of cases in the research. The findings reported in this article support findings from other studies (Alabastro et al., 1995; Bruun et al., 2014; Gebhardt et al., 2014) that visual architecture modeling is a powerful means of supporting and driving the development process by affecting both the communication and decision making in a positive way. Using it in both physical and electronic versions expanded the use of the tool beyond being the property of a single person and encouraged participants in meetings to discuss and make the changes needed directly into the TePPAT.

As the purposes of prototypes can be learning, communication, integration, and milestones (Ulrich and Eppinger, 2008), the findings from the cases can be argued to strengthen these purposes. The three sections, combined in the TePPAT, have also shown the worth of allowing abstraction and detailing in a single overview.

Whereas other tools are used for different system views, the TePPAT is used in a multi-layered approach at three levels: purpose, concept, and architecture. Three dimensions add to the multi-layered aspect, the first being the linking of purpose, concept, and architecture descriptions in the TePPAT; the second being the layers used in the architecture section, and the third being the time dimension.

The case construction for this article followed a multiple-case design, testing the use of the TePPAT. The strength of the cases was the shared context, that is, the integration of the same novel technology into concurrent technology prototypes for different projects. This allowed multiple cases of analysis to be used to test the repeatability of the use of the TePPAT, giving a more robust overall study (Herriott and Firestone, 1983). A shortcoming has been the limited number of cases. More cases are required to support the observations and effects of using the TePPAT through repeatability. The results presented from the case studies have mainly been qualitative, based on participant observation, meeting notes, and informal interviews. These sources of data made it possible to cover events in real time and provided insight into behavior (Yin, 2009). Further quantitative measures would provide a stronger indication of the effects of using the TePPAT. However, two things complicated the collection of such data: the project was still ongoing and there were few cases for comparison.

## Conclusion

In this article, two main contributions are made. The first is to the vocabulary of prototyping, by the introduction of the term *technology prototypes*, covering prototypes developed to investigate and demonstrate the performance of a novel technology. The second is to the modeling and management of technology prototypes by the introduction of the *TePPAT*.

The TePPAT provided support for the development of technology prototypes in a Danish PPP technology test and evaluation project where the application of a novel technology was tested in multiple, heterogeneous instances. The industrial implementation in the IFDen project cases indicated the usefulness and effects of the TePPAT. Through the modeling of the Purpose, Concept, and Architecture sections, the TePPAT can be used to describe the *idea with* and the *idea in* the technology prototypes. It is concluded that use of the TePPAT can be correlated with improvements in communication, system overview, and reasoning, when working with technology prototypes.

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### Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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# 10.3 Paper C: Identification of Critical Technology Building Blocks

Submitted to a peer-reviewed journal, 2015

Authors: Ravn, P.M., Mortensen, N.H., Hvam, L.

**Abstract**

In order to have a better base for decisions, R&D managers need to know what the critical areas of development are in relation to the technologies they develop, mature, and include in the portfolio. As most of the technologies in a company have the potential to have a significant impact on competition, the challenge is to know how to identify and prioritize the development tasks. This paper suggests a framework for identification and analysis of a product portfolio, with special emphasis on identifying critical technology building blocks. Current approaches lack such views and by focusing on these, potential make or break decisions are better supported. In order to overcome challenges in a company where multiple technologies and products are developed concurrently it is suggested to adopt the proposed framework to clarify where in the portfolio the technology needs critical attention for the next development steps. The framework is based on methods and theories in literature. The analysis of the portfolio is done through the framework in three steps: by creating an overview of the portfolio encompassing product and technology, assessing the elements in the overview with assessment metrics, and by using property chains to identify critical technology building blocks.

# Identification of Critical Technology Building Blocks

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In order to have a better base for decisions, R&D managers need to know what the critical areas of development are in relation to the technologies they develop, mature, and include in the portfolio. As most of the technologies in a company have the potential to have a significant impact on competition, the challenge is to know how to identify and prioritize the development tasks. If possible, an effective strategy can be defined. This paper suggests a framework for identification and analysis of a product portfolio, with special emphasis on identifying critical technology building blocks based on reasoning about properties. Current approaches lack such views and by focusing on these, potential make or break decisions are better supported. It is suggested to adopt the proposed framework to clarify where in the portfolio the technology needs critical attention for the next development steps. The framework is based on methods and theories in literature. The analysis of the portfolio is carried out through the framework in three steps: by creating an overview of the portfolio encompassing product and technology, assessing the elements in the overview with assessment metrics, and by using property chains to identify critical technology building blocks.

Keywords: technology development; technology building blocks; product properties; property reasoning; portfolio management

## 1 Introduction

In order to have a better base for decisions, R&D managers need to know what the critical areas of development are in relation to the technologies they develop, mature, and include in the portfolio. For large investments in technology the objectives are to reduce risk, whilst increasing performance (Mankins 2009a). If successful, the potential output is breakthrough inventions (Ahuja and Lampert 2001).

The challenge is to know how to identify and prioritize the development tasks as most of the technologies in a company have the potential to have a significant impact on competition (Porter 1985). This requires an understanding of the technologies, but also knowledge of how to perform an assessment. Current approaches can be used to identify and prioritize technologies (Mankins 2009a; Clausing and Holmes 2010).

However, these do not take the key properties of a product into account. The product properties have high relevance in the assessment and positioning of a novel technology in a portfolio as these often are used for comparing whether a technology is competitive against other technologies. Therefore, the focus should be on properties and the link to the elements of technologies that carry these.

In this paper such elements of technology are referred to as Technology Building Blocks (TBB). They combine two different views on a technology: knowledge of parameters enabling the capture of a natural phenomenon (product related) and knowledge of processes to realize the technology (production related). A specific type of TBB is of key interest in this paper: Critical Technology Building Block (CTBB). Here, CTBBs are defined as those essential for increasing key product properties. If the CTBBs cannot be identified and targeted, there is a risk of making the wrong strategic decisions.

A three-step framework is proposed for the identification of CTBBs. Step one: create an overview of the forming portfolio for the company. Step two: assess the contents of the portfolio. Step three: use property reasoning to identify CTBBs by use of chains through the portfolio.

### *1.1 Challenges in identifying critical technology building blocks*

The following challenges for identifying technology building blocks have been found in the literature:

- By splitting technology development and product development in the organization, there is a risk of inefficient transfer of technology and lack of synchronization (Wood and Brown 1998; Lakemond et al. 2007; Nobelius 2004; Holt 1991).

- A large part of the value chain may have to be developed from scratch when a novel technology is used for definition of new products (Wood and Brown 1998; Tryson and Kiil 2010).
- There are disconnects between the strategies of the business and where the money is spent (Cooper, Edgett, and Kleinschmidt 2001).
- Resources need to be spent with the best possible chance of progression on the right tasks (Mankins 2009a).
- Increasingly high level of complexity and high level of technical novelty in products affect technology integration (Iansiti 1995).
- There is a high dependence on the competence and the initiative of individual managers and engineers (Holt 1991; Mankins 2009b).

### *1.2 Requirements for a framework*

The purpose of the framework is:

- To identify a uniform structure describing technology building blocks in the product portfolio including different levels of the value chain to allow overview of all entities to form the best basis for decisions.
- To enable an assessment of the portfolio and development status.
- To provide a basis for strategic decisions of what products and technologies should be focused upon.

A framework for identification of CTBBs should enable R&D managers to:

- Identify a structure that can describe the relation between the products and technologies in the company portfolio, as technologies are developed with an intended use in an organization.

- Assess the development, as it is critical for senior management to be able to choose between alternatives (Mankins 2009a).
- Trace product properties through the value chain, as these are key to positioning on the market (Mørup 1993).
- Identify the technologies that are the main contributors to the next level of performance within a certain property, as these can be defining for the technology strategy.

### *1.3 Structure of the paper*

First, the research methodology is introduced followed by a state of the art review. Then the framework is introduced, and an example is given of the use. Field testing of the framework is presented by using an industry example of the Dielectric Electro-Active Polymer (DEAP) technology development project. Finally, the discussion and conclusion make up the final sections of the paper.

## 2 Methodology

The Design Research Methodology (DRM) approach was used, from Research Clarification (RC) to initial Descriptive Study II (DS-II) (Blessing and Chakrabarti 2009).

### *2.1 Literature study*

A literature study was conducted in two parts: state of the art within modelling approaches and theoretical base for the framework. Literature was gathered over two iterations: a broad, initial iteration followed by a more detailed search. Here, the abstract was read and papers of interest were included in the literature study.

### *2.2 Building of the framework*

The base skeleton of the framework was created, based on literature. Literature on product structure relations and product/technology relations was used for the first step of the framework. Literature on assessment metrics was used for the second step, and literature on product properties, property reasoning, and engineering design, was used for the third step.

### *2.3 Testing and evaluating the framework*

A concluding, four-year, 13 M€, industrial project was used to test the framework. Data was collected from multiple sources: a joint data repository for 10 work packages, individual repositories, meetings, and through informal interviews. The framework was tested to verify fulfilment of the requirements. Finally, an evaluation of the framework was made in a workshop by four key persons from the industry project.

## 3 State of the art

The state of the art is focused on four main areas based on the requirements for a framework: how to capture attributes of a system, i.e. structure and behaviour of a system, single and multi-product development, how to include technology, and how to assess and prioritize development tasks.

### *3.1 Structure and behaviour of a product system*

A product system can be described from two perspectives, the structural characteristics (structure) and the functional properties (behaviour) (M. Andreasen, Howard, and Bruun 2014).

#### *3.1.1 Structure of a product system*

In design structure matrix (DSM) (Steward 1981) approaches, products are decomposed into smaller components or systems with relations between these indicated. Ordinary DSMs are used to decompose and relate parts, requirements, processes etc., for instance as proposed by Eppinger and Browning (2012) and Bonev et al. (2013), and can represent different levels of a system (Tilstra, Seepersad, and Wood 2012), or to indicate product variety (Luh, Ko, and Ma 2011). Quality Function Deployment (QFD) is used to convert customer demands into engineering requirements. Modular Function Deployment (MFD) is used with module drivers to view the flow and refinement from customer demands to designed modules (Nilsson and Erixon 1998). The product family master plan (PFMP) (Harlou 2006) is used to map structure from three points of view and the relations between these: customer, product, and production. Bonev et al. (Bonev et al. 2013) combined the matrix approach with the PFMP in the Product Requirements Development Model to investigate the effect of requirements on the product architecture.

### *3.1.2 Behaviour of a product system*

The behavioural view of a system is here divided into functions and properties. Function diagrams give a function structure with sub-functions connected by energy, material, and energy flows (Ulrich and Eppinger 2008). Both Function-Behaviour-State (Tomiyama, Umeda, and Yoshikawa 1993) and Function-Behaviour-Structure (Gero 1990) apply function modelling to reason about products. Organ diagrams have been used to model the “organs” of a product (Harlou 2006). More recently, the organ diagram has evolved to accommodate switching between different system views (Bruun, Mortensen, and Harlou 2014).

Function and property reasoning are found with a sound base in engineering design (Howard and Andreasen 2013; Vermaas 2013; Gero 1990). Andreasen (M. Andreasen, Howard, and Bruun 2014) contributed with the articulation of the Domain theory and the link-model where the latter specifically can be applied for reasoning about functions and properties of both the product and the use activity. Property reasoning and property modeling (Myrup Andreasen, Thorp Hansen, and Cash 2015) provide insight into the background for this type of mind-set approach with a description of property decomposition patterns to allow an identification of properties or qualities of sub-systems (Mørup 1993). Jensen et al. (Jensen, Parslov, and Mortensen 2015) used property models to decouple interrelated dependencies to enable carry-over of test documentation between product families. In the Characteristics-Properties Modelling (CPM) and Property-Driven Development/Design (PDD), a distinction is also made between the characteristics and the properties of a product (Weber and Deubel 2003; Weber 2005).

### *3.2 Single and multi-product*

For large, single systems UML or SysML modelling languages can be used to describe the system of interest and the interaction between different views on the system, often based on the construction of meta-models (Andersson et al. 2010). To simplify the, at times, large system descriptions, Borches (Borches 2010) proposed the A3 overview on which a single page is used to represent the system in focus to have a manageable architectural representation (Bonnema, Borches, and Houten 2010).

For multi-product development the program architecture approach aims to optimize the product portfolio by mapping the program architecture, consisting of market, product, and production architectures (Hansen 2014). The integrated PKT-approach aims to achieve external product variety for the market with small internal variety of components and processes in the company (Krause et al. 2014). The Brown-field process contributes with a design process to modular product family development via design information elements (Pakkanen 2015).

### *3.3 Including technology*

When looking into literature, different understandings and classifications of technology and technology development can be found (Burgelman, Christensen, and Wheelwright 2009; Fusfeld 1978; Högman and Bengtsson 2010; André et al. 2014). Dosi (Dosi 1982) argued that physical devices embody the achievements in the development of a technology in a defined problem-solving activity. Meyer and Lehnerd (Meyer and Lehnerd 1997) included product and production technologies as a base for product platforms. Thus, a producing firm must consider two dimensions of a technology: a product dimension (the principle of how to harness a natural phenomenon) and the production dimension (the transformations related to the making of the principle) (Mørup 1993; Greis 1995). Schulz et al. (Schulz et al. 2000) sees Process Technologies, together with Management & Organisation and Methods and Tools, as secondary technologies that enable product technologies (primary technologies).

Different approaches are found to include technology indicating the thoughts of structure and the application of technology. Bitzer et al. (Bitzer, Vielhaber, and Dohr 2014) discuss Technology Objects and Jeong & Yoon (Jeong and Yoon 2014) utilize an ontology of technology for structure. Huang et al. (Huang et al. 2011) utilize R&D to applications cross-chart to connect technology and application.

Platforms have also been used at a technology level, i.e. technology platforms, where models and frameworks have been presented (Levandowski et al. 2012; Simpson et al. 2014; Nasiriyar 2009; Nasiriyar 2010; Wonglimpiyarat 2004; Kristjansson, Jensen, and Hildre 2004).

### 3.4 Prioritizing and assessing tasks

Roadmapping is a widely used tool to prioritize and relate time-dependent task-deliveries. It is used to map out and prioritize deliveries from projects, departments, tasks etc., and indicate the relations to a recipient. The number of levels of coordination can vary by project type (Mortensen, Harlou, and Andreasen 2005). Vojak et al. (Vojak and Chambers 2004) proposed a methodology to investigate possible disruptive technologies. Zurcher and Kostoff (Zurcher and Kostoff 1997) provided an approach to model technology roadmaps. Jeong and Yoon (Jeong and Yoon 2014) presented patent roadmapping and the relation to technology roadmaps. Technology roadmapping has also been used as a method for technology push (MTP) (Caetano and Amaral 2011) and as a model for disruptive technology (Walsh 2004).

In order to assess systems under development, Mankins (Mankins 2009b; Mankins 2009a) suggested technology-centric measures with the technology readiness levels (TRL), technology need value (TNV), and research and development degree of difficulty (R&D^3). Clausing and Holmes (Clausing and Holmes 2010) proposed the technology readiness assessment (TRA) matrix. In the early phases also integration readiness level (IRL) and system readiness level (SRL) can also be considered (Sauser et al. 2008).

### 3.5 A need for a different approach

When comparing with the requirements posed for the framework in section 1.2, the following is argued. Few of the presented modelling approaches focus on the handling of discussions evolving around the technology-based choices needing to be taken in the development. Only a few frameworks and methodologies include reasoning about properties in a holistic manner and include technology. Concluding the review, a framework to use as a basis for taking decisions on further development with focus on technology, based on property reasoning, is absent.

## 4 Framework for identification of critical technology building blocks

In the following sections the three steps for the framework are introduced.

### *4.1 The framework: overview, assessment, and reasoning*

The framework is formed of the three main steps:

- Step 1: Creating the portfolio overview – where the base structure is described on multiple layers.
- Step 2: Assessing the system elements – where the contents of the overview are assessed.
- Step 3: Reasoning about properties – where the desired properties are projected down through the portfolio overview.

The combination of the three steps will provide a structured way of representing the technologies and capabilities in the company as well as providing a sound base for a technology strategy definition. Inputs and outputs can be seen in Table 1.

Table 1 around here

### *4.2 Step 1: Building an entity-relation overview of the product portfolio including technology*

The main structure of the overview is split into two main dimensions: product and technology, and follows a diabolo structure (Erens 1996), as illustrated in Figure 1. The structure is linked to the granularity view of a product and the tiers get input from each other. A part of the overview can be singled out, with the greyed-out structure, in order to focus on parts of the development.

Figure 1 around here

Reading from the bottom of a tier the technologies are represented by TBBs. These are realized in components. The components (here referred to as modules, organs, and parts (Gershenson, Prasad, and Zhang 2003; M. M. Andreasen 2011; Meyer and Lehnerd 1997)) make up a product family (a group of related products (Simpson, Siddique, and Jiao 2006)), based on an architecture aimed at a specific market. These related products are in the framework illustrated as variants in the framework.

In the overview platforms can be made out of components (Meyer and Lehnerd 1997), albeit not being the main focus. Likewise technology platforms can be indicated in the technology dimension. The top tier of an overview represents the product in which the technology is integrated. This tier is also the starting point for the last framework step, the Reasoning.

### *4.3 Step 2: Assessing the current situation in the portfolio*

The assessment is used to give knowledge on the status of the development in the overview. For each of the elements, the completed tasks are represented. This will give an indication to the project management to illustrate the status of each element. Additionally, performance metrics are indicated here (Mankins 2009a).

### *4.4 Step 3: Property reasoning to identify critical technology building blocks*

Two types of property decomposition patterns are considered, as illustrated in Figure 2: Property Delivery Chain (PDC) made bottom-up and Property Target Chain (PTC) made top-down. PDCs track the deliveries made based on the solutions chosen. One solution may contribute with multiple properties. PTCs are used in this step to track properties down to CTBBs.

Figure 2 around here

The task of identifying the PTC for a certain property starts from the top tier. Here the properties, guided by requirements for instance are found. These are transformed to product property requirements for the lower tiers, based on decomposition of the requirements.

A deep knowledge is required about the portfolio to perform this reasoning. Understanding the relation between properties and characteristics will assist the reasoning in this step as the characteristics that define the components play a role in the definition of the properties. The main reasoning is made by setting a number of requirements that guide the identification of the CTBBs.

***4.5 Example of using the framework***

Consider the following example of a badminton racket manufacturer. A competitor has introduced a new type of frame obtaining better racket frame flexibility. The manufacturer wants to introduce a new type of frame to stay competitive. Step 1-3 could be as illustrated in Figure 3.

Figure 3 around here

Step 1 presents four tiers of granularity from the badminton racket (tier 4), through frame (tier 3), and down to shaft (tier 2) and material (tier 1) as these are related to the frame. A newly developed shaft (part of the frame) is shown to illustrate the assessment (Figure 3, middle). It is based on a new shaft core material. The shaft is evaluated in different dimensions, and the completed tasks noted.

The frame from the competitor offers more power to the players in their shots. The value proposition that needs to be focused upon is linked to the property "Flexibility" for the racket shaft. By trailing the PTC (Figure 3, right) the shaft core technology is identified to be the CTBB in the portfolio for the flexibility property.

Having introduced the framework and given an example of the use, the next section will introduce experiences from field testing the framework.

## 5 Field testing in a technology push setting

A test of the framework was made in an industrial project to verify the applicability of the three framework steps.

### *5.1 The situation – development on all fronts*

A spin-out company aimed to commercialize the DEAP technology based on a patent (Tryson and Kiil 2010). The DEAP technology had the potential for multi-industry application as a transducer sub-system (actuator, generator, or sensor). A joint technology development project between different industries and universities was created to mature the technology over a 4-year period (2011-2015). The development included a substantial part of the value chain (Tryson and Kiil 2010), ranging from the core polymer material, through the transducer concept definition, and over to testing of the product concepts in four industrial applications (Sarban 2013).

There was a need to lay out and display the portfolio forming around the DEAP technology on multiple tiers to enable strategic decisions for further development. Overviews had until then been made in each of the work packages, but these overviews were to a degree implicit, resulting in a fragmented and incomplete overview of the development tasks.

### *5.2 Step 1 and 2: Identifying and assessing the portfolio structure on multiple levels*

The core technology for a DEAP transducer is the EAP technology. This example is concentrated on only a partial view of the full overview, i.e. the electrical driver for the DEAP transducer was not included as the main properties of the DEAP product were found here (Tryson and Kiil 2010). The overview levels followed the levels of the project, i.e. on T1, the polymer material, on T2 the EAP film, on T3 the DEAP transducers, and on T4 the applications, as seen in Figure 4.

Figure 4 around here

Due to project confidentiality, the overview has been simplified in this example. The basic overview was based on data found in the joint project data repository, individual repositories, meetings, and through informal interviews. The data types were technical reports (repositories and meetings), overview descriptions, in presentations (repositories and meetings) for example, and relational descriptions (meetings and interviews). The overview was made by the researchers in collaboration with participants of the work packages. By proposing structures and relations, discussions were found to initiate on what implications the previous decisions had created.

As the main focus for the development was on tiers 1-3 in the development, tier 4 had a higher abstraction level. On the 4th tier, the applications, architecture models were used for documenting the relations in four technology prototypes, i.e. prototypes built for assessment of performance of the DEAP transducers in a product concept formulated with the application companies (Ravn, Gudlaugsson, and Mortensen 2015).

In the project, the assessments of the portfolio elements were conducted by describing completed tasks and by using TRL as a performance measure (see Figure 4).

### *5.3 Step 3: Property reasoning to identify property target chain*

From the top down, the PTC reasoning, a number of key properties were used from the development up until that point in time. The properties were based on lessons learned through the three development cycles in the four applications. The properties were then guided down through the overview and for each level a set of requirements was discussed by the project participants, based on the implication the increase of property would have on that specific element on that specific tier.

Two PTCs are illustrated in Figure 5. The properties high force density and high dynamic had been identified as key properties on tier 4.

Figure 5 around here

For the first example, a high force density was sought as a value proposition. From here, guiding requirements were used to facilitate the property decomposition represented by the PTC. The PTC was tracked through a specific product family entity on tier 3, down to a CTTB A on tier 2 and a CTBB B on tier 1. CTBB A was related to the electrode deposited on the polymer film and CTBB B was related to the material composition technology.

For the second example, a high dynamic was sought as a value proposition. The PTC was tracked through a specific product family entity on tier 3, down to a CTBB B on tier 1 – the material composition technology.

Having identified the CTBBs, the following discussion covered the next action steps:

- The material (critical technology building block B) should be approached with a platform approach in the next development task. Thereby different requirements could be fulfilled instead of a “fits all” material. By making different material platforms, performance increase was expected.
- The electrode (critical technology building block A) should look to be improved if the goals of durability and robustness were to be achieved.

As an output from the framework, prioritization of resource allocation and identification and specification of action steps were made possible.

### *5.5 Specialist evaluation of the framework*

A workshop was held to evaluate the framework. The participants articulated their opinions about the value of the framework, some of which are presented here:

- "I realize that some tasks form around a whole new technology by themselves."
- "The framework is really strong for cutting to the bone for the next step (of development)."
- "We need to discuss whether some technologies are product or production related."
- "The framework is best suited for a top-down approach."
- "For the technological decisions, we now have an idea of where to focus."
- "By tracking the value propositions we can see the impact."

The statements indicate that the participants, albeit their deep knowledge about the technology on the different tiers, evaluated the framework as being useful for creating a good base for decisions.

### *5.5 Summarizing the use of the framework*

With the field testing case, it has been illustrated that the framework fulfilled the purposes to: a) identify a uniform structure over multiple value chain levels, b) enable assessment of the portfolio and development status, and c) provide basis for strategic decisions.

It was found that the overview in step 1 could be used to describe the structure of the four tiers and the relations between these, as well as describing the relations between the product dimension and technology dimension. Using assessment in step 2 gave the status of the development and step 3, with the use of two examples, was illustrated to enable an identification of CTBBs on different levels of the value chain by use of PTCs.

### *6 Discussion*

Compared to other approaches, such as the ones mentioned in Section 3, the proposed framework includes to a higher degree, the technologies in the company. Rather than having product optimization in focus, the framework is focusing on the inclusion of technology building blocks and specifically targeting CTBBs by the use of PTCs. This, combined with the aforementioned approaches, seeks to support the definition of a viable and sound development strategy.

#### *6.1 Fulfilling the requirements*

The framework provides a holistic approach to viewing the portfolio including technologies under development and provides the means to navigate in the development. With the field test it was illustrated that the framework fulfilled the purposes from Section 1.2. The example and field testing illustrated that the framework was able to include multiple tiers, allowing assessment, as well as successful identification of CTBBs. This speaks of fulfilment of the requirements for the framework. Additionally, the challenges from Section 1.1 are addressed in the framework. The overview allows for identification of the relations between the entities in the portfolio and thus bringing transparency for management. The assessment enables a status to be given to each of the entities being developed. The reasoning enables identification of the critical areas for key performance.

#### *6.2 Evaluation of research*

The research presented in this paper has a natural limit with it being tested on a single case. However, it is assessed to be representative for other companies trying to establish a portfolio based on a novel technology. The validation of the framework is preliminary and further testing is needed for increased insight into the identification of critical technology building blocks. A number of assumptions were made for the framework. It was assumed that for both technology push and market pull settings, potential products in which the technology can be used are identified. Therefore, another assumption is that the potential products are known. As the framework uses input from possible applications already identified, the selection of applications was not covered in this paper. Future research may include the coupling between the framework and pairing with possible applications.

### *6.4 Additional case observations*

It was found that terminology had a large impact, both in the theoretical and practical models, as technology is individually interpreted. The preparatory work needed to create consensus on the elements and relations in the overview can be a large task, and should be undertaken by an architecture and platform department or alike for maximum communication throughout an organization.

In the lower tiers of the overview it became harder to apply the framework structure. This may be due to reaching a level where the components are closer to natural phenomena and basic materials.

At the beginning of the industrial case it was a major challenge for the different development teams when needing to keep the overview. Ten work packages had to coordinate and cooperate towards common goals, so that ideas and decisions, and ultimately the overall strategy were in alignment.

## 7 Conclusion

In this paper a framework was presented to provide a structured way of analysing a product portfolio to identify Critical Technology Building Blocks (CTBBs) that enable prioritization of the development. The three-step framework consisted of: the creation of an overview, assessment of the elements in the overview, and finally the use of Property Target Chains (PTCs) to enable identification of CTBBs. The contents of the framework have been devised from literature, described and a general example was used to describe the general approach and method to using the framework. The framework was tested in an industrial technology development project in which transducers based on the DEAP technology were built and tested. The framework has the potential to increase the efficiency of R&D, as application specialists evaluated the framework to be a strong framework for cutting to the key focus of the development. Further research should be used to investigate the use dimensions of the framework in other settings and to validate on a broader scale. Further work will include testing on additional projects to validate the findings.

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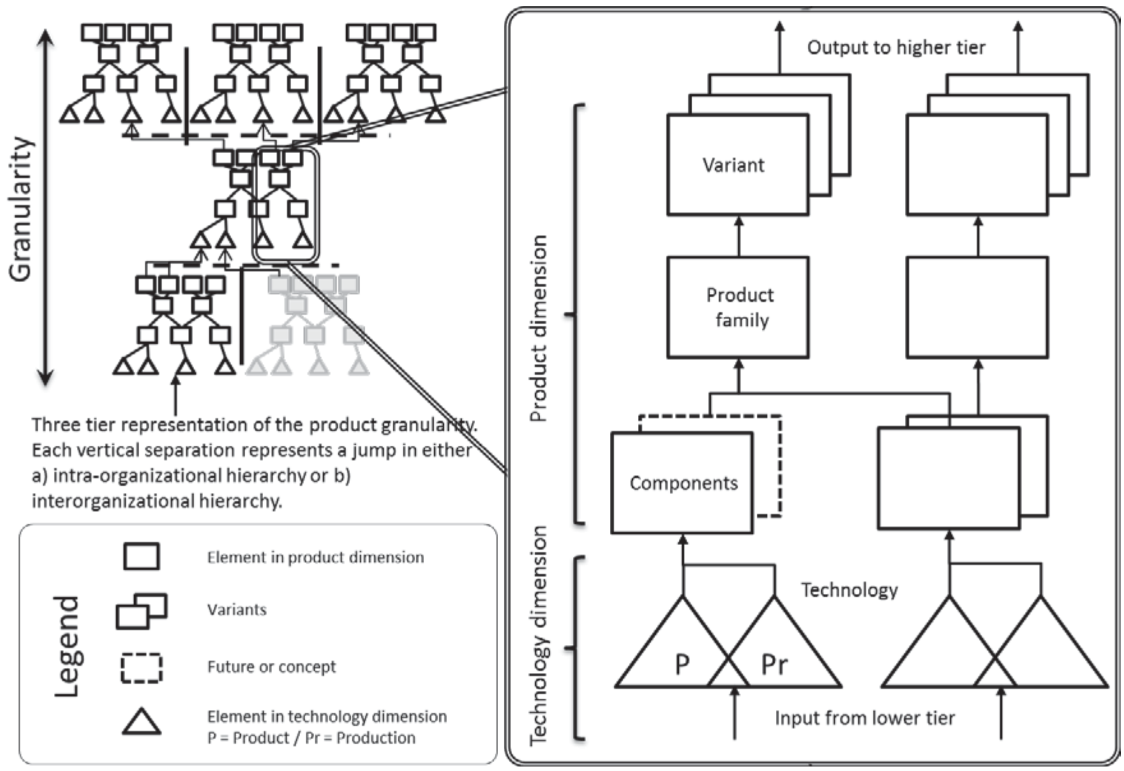


Figure 1. The structural part of the system. A representation of a product decomposition in four tiers each in four levels: technology, component, product family, and product variant.

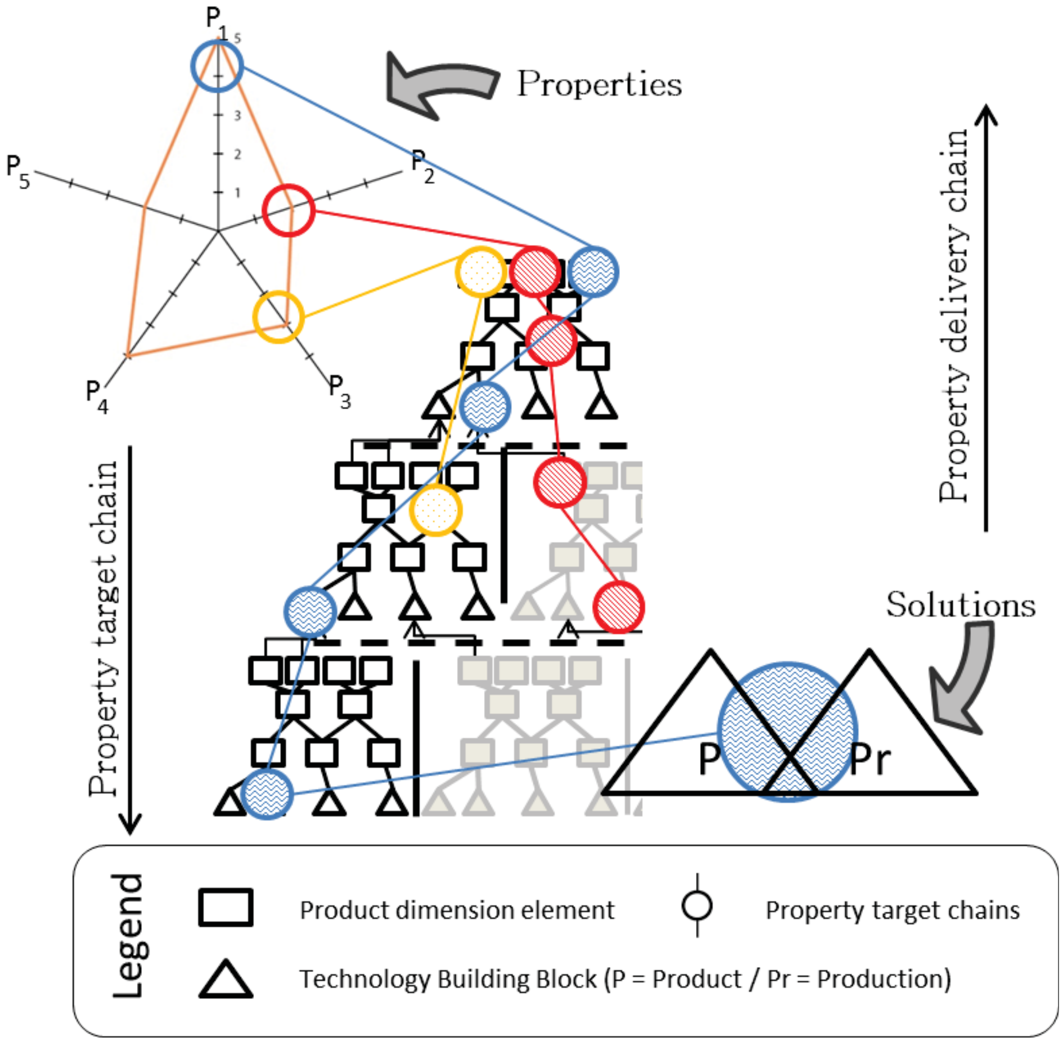


Figure 2. Two types of property relation chains A) Property target chain (top-down) B) Property delivery chain (bottom-up).

Table 1. The three steps of the framework and their inputs and outputs.

| Step | Input | Output |
|---|---|---|
| Overview | Technologies, components, product families, and variants<br>Existing and upcoming solutions | Portfolio overview<br>Variant / family / component / technology relations |
| Assessment | Performance assessments<br>Completed tasks | Current development status |
| Reasoning | Identified key properties | Critical Technology Building Blocks |

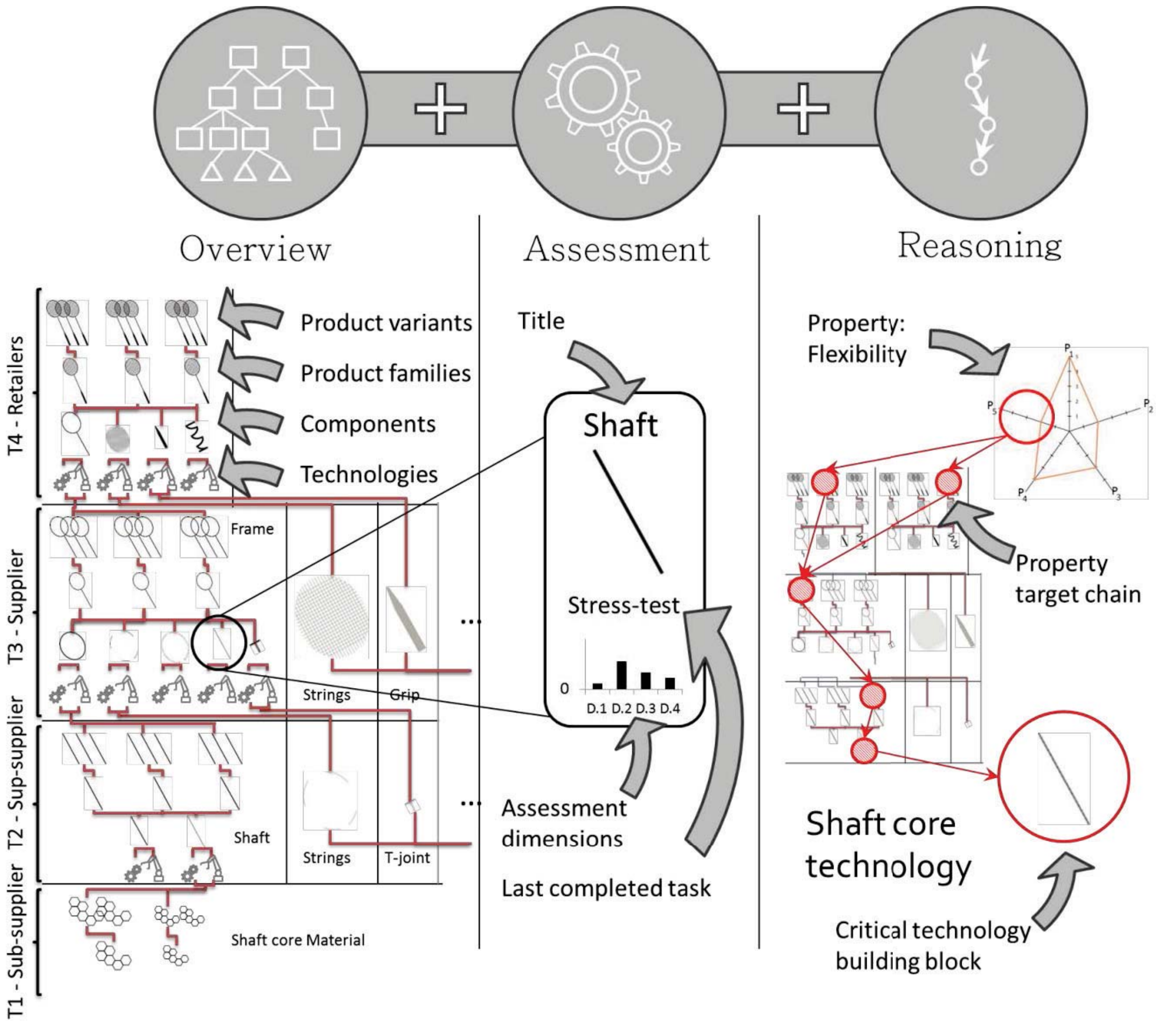


Figure 3. The technology focus framework exemplified with a badminton frame manufacturer.

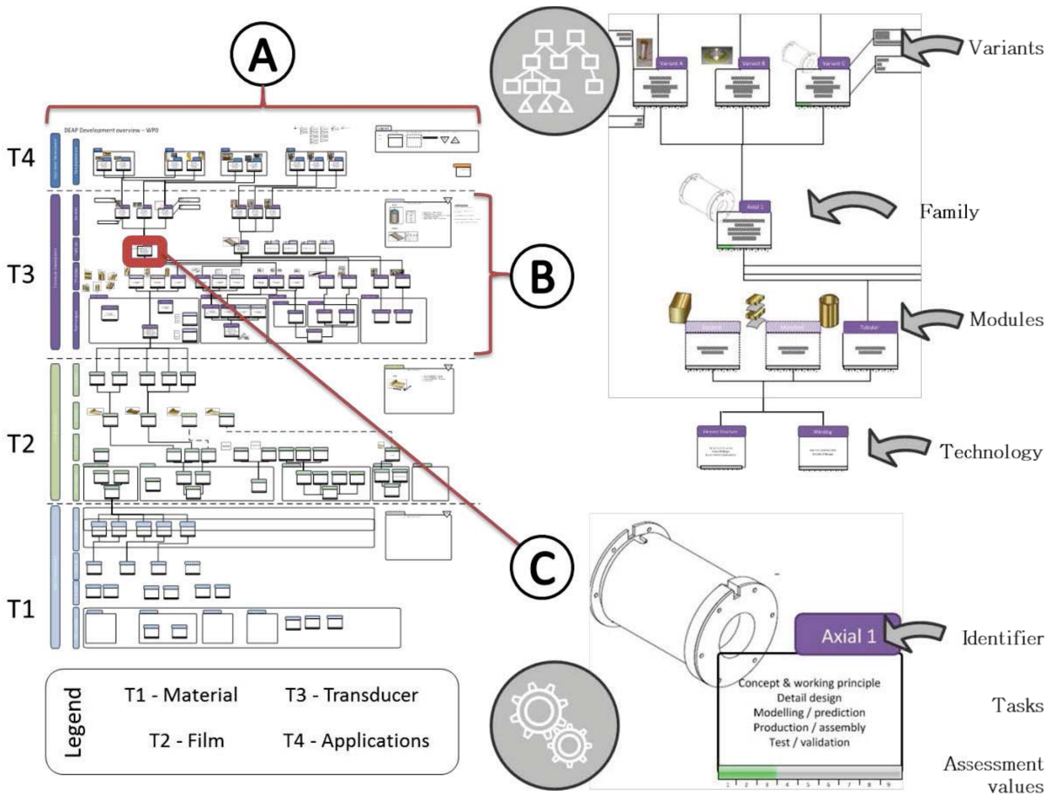


Figure 4. Example from the case: a) identification of structure on multiple levels, b) example of structure, and c) example of assessment.

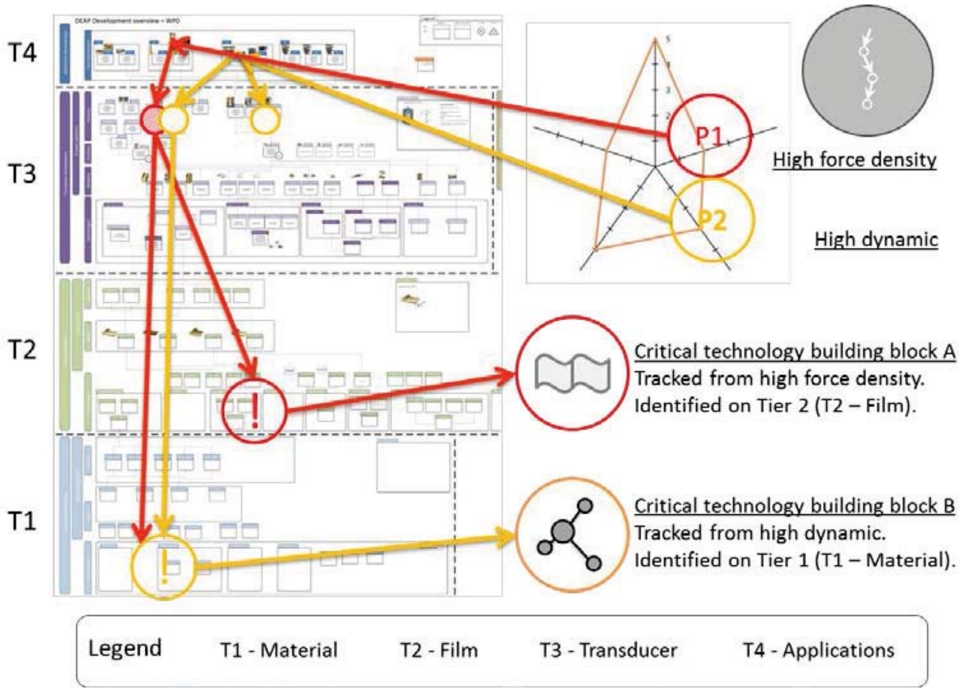


Figure 5. Identification of two critical technology building blocks.

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# 10.4 PAPER D: VISUAL MODELLING OF PILOT PRODUCTION TO SUPPORT DECISION MAKING IN PRODUCTION DEVELOPMENT


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**Abstract**
This paper presents the development of a visual production model that emphasizes product variant creation, product characteristics definition, and benefits from updates to the production equipment. The implementation of the model to model three instances of a pilot production ramp-up, including investigating the needs for a model, the data collection, the modeling process, and the experiences from the implementation, is presented. The paper concludes that the model makes tacit knowledge of stakeholders explicit and supports communication of the intended benefits of the production ramp-up.

INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

# VISUAL MODELLING OF PILOT PRODUCTION TO SUPPORT DECISION MAKING IN PRODUCTION DEVELOPMENT

P. M. Ravn, T.V. Guðlaugsson, N.H. Mortensen

*Keywords: Decision making, visual modelling, pilot production*

## 1. Introduction

Industrial production faces a challenge of optimisation in almost every aspect, to live up to the continuous demand of increased capacity. Some of the production process issues that are under continuous focus include dimensional tolerances and surface finish, production quantity, production rate, lead time, and robustness and process [Kalpakjian and Schmid 2006]. However, before this can be achieved, the production processes need to be matured to a point where product quality requirements and production capacity needs can be met. When the product to be produced is based on a new technology, never produced in large quantities before, the first priority is to prove that it can be produced at all.

As a central part in production process development, a pilot production can be used as a prototype for the production process, where the processes can be developed, tested, and refined [Oberle 2013]. To be successful, a pilot production should first and foremost be able to demonstrate that the intended products can be produced to the required quality levels. Here, the focus is on achieving control of individual processes, demonstrating scalability of critical production processes, implications of process parameters on product characteristics, and weaving out critical faults in production processes, to a level where the results can provide a foundation for decisions on investing in a full capacity production facility [Oberle 2013]. Therefore, making the right decisions in the pilot production can be crucial for the success in production process development.

A common way of supporting decisions in production is to capture the production process design with a desired perspective. Production process modelling has been done for decades with flowcharts [Gilbreth and Gilbreth 1921], and a large number of different other tools, and most tools are found to be aimed for communicating specifics about the process for further analysis. Most process modelling approaches are aimed to support industrial production and thus highly standardized. Visual modelling approaches have previously been shown to support decision making in production process development projects [Alabastro et al. 1995] and product development projects [Mortensen et al. 2008]. This paper presents the practical experiences from supporting and communicating the decision making for a pilot production setup in a technology development project by visual modelling. The modelling is based on the generic production flow [Mortensen et al. 2011], but in a setting where neither product nor production is yet defined. These results are part of research into the application of visual modelling tools to support decision making in production process development.

The paper is structured as follows: Section 2 highlights and discusses production process modelling methods found in literature and industry. Section 3 presents a case, in which production of a new technology is being developed in order to demonstrate that production of a new Electro-Active-Polymer (EAP) film technology can be scaled, while increasing production quality and EAP film performance. Section 4 presents findings in the case. Section 5 discusses the findings and presents future work. Section 6 presents the conclusion of the paper.

## 2. Production modelling approaches

This section will review some production modelling approaches found in literature and industry today and discuss their application. The focus will be on diagrammatic modelling approaches [Vergidis et al. 2008].

Flow charts are one of the simplest ways to graphically model production processes [Meyer et al. 2006]. In their most basic form, they comprise no graphical elements other than standardized flowchart symbols, which give no detailed information on the processes that they depict. Within the processing industry, process flow diagrams include standardized abstract graphical symbols to denote important processes and equipment [Silla 2003]. Although they provide more graphical information to the reader, a full understanding of the production process depicted cannot be achieved without knowledge of the symbols, and the processes represented by them. This reduces their effectiveness when they are used to communicate the production process to persons unfamiliar with the symbolism or that lack specialist knowledge of the processes.

The Integration Definition (IDEF) suite and the Unified Modeling Language (UML) have been demonstrated for modelling of production process design [Perera and Liyanage 2000] [Zhang et al. 2007]. Where IDEF has been developed and applied over a number of decades [Spur et al. 1996], the UML is a more recent approach. Both make use of a number of different diagram types to model distinct aspects of a system, but only with standard, graphically simple, notations defined for each modelling approach. Their application to modelling production systems in detail has been shown, from different perspectives, and they are often used in conjunction with process simulation tasks. [Oscarsson and Moris 2002]

The generic production flow is a visual modelling approach that has been used in the development of product platforms and families [Mortensen et al. 2011]. The generic production flow visualises the production flow for product variants, through visual modelling of process steps and the resulting output, as well as identifies common process steps. One of the experiences from the application of the model, together with product and market architectures, was reported to be "Improved synchronization between product- and production development." [Mortensen et al. 2011, p. 1] The utilisation of the generic production flow has proved beneficial in the context of product families, but the flow model has not been investigated for use in a pilot production setup.

For the application of most modelling principles, a number of general considerations have to be made. The level of detail to be captured in the model should be defined. The purpose of the modelling should be defined, so the model covers the needs from the users of the model. Considerations about what points in time that should be captured are beneficial. Some projects may have interest in defining the current situation, where others may gain from modelling desired, future setups. [Browning 2010]

Visual modelling using graphical elements, icons, to depict process equipment, as part of a simulation model development, has been shown to benefit understanding across knowledge domains and increase commitment from stakeholders [Alabastro et al. 1995].

The generic production flow has been used successfully within product-family development and includes a focus on product variant creation. In the pilot production development of focus in this paper, the ability to produce product variants, and the determination of product characteristics in the production process, is of a high priority. The generic production flow is therefore a solid foundation to build upon for this purpose.

## 3. Case: visual modelling of the EAP film production

The production of a new technology is being developed by Danfoss PolyPower in order to demonstrate that production of a new Electro-Active-Polymer (EAP) film technology can be scaled, while increasing production quality and EAP film performance [Kiil 2009]. The production of the EAP film has through the past ten years gone from lab production setups to a pilot production setup with the goal of reaching a matured EAP production setup capable of mass-producing the EAP film.

Danfoss PolyPower has, together with a consortium of companies and universities in Denmark, defined a five year, 12 million € project supported by the Danish National Advanced Technology Foundation (DNATF), to mature the EAP technology. The project includes multiple work packages working in parallel to develop materials, production processes, products, mathematical modelling, and prototypes for applications of EAP future products. The modelling task described in this case was initiated by the project manager, accommodating wishes from the case project steering committee, to support the management of the tasks involved with production process development in the project, and the implications on the production. The decision was to model the pilot production setup, with the intended developments in the DNATF project, to support the communication between collaborators and decision-making in production process development tasks.

### 3.1 Method

The development of the model was carried out in three draft phases, with the drafts reviewed through workshops; the final draft was presented at a project symposium. Figure 1 shows the process followed in the case study and highlights major phases in the development of the model: draft work on the model, workshops for discussion and verification, and feedback. To create a frame for gathering the required data needed for the modelling, with a verified content, data triangulation was used [Yin 2009]. Different sources of evidence were used for data triangulation: documents (previous production process diagrams), interviews (with production manager and production team), and participant observation (as active contributors in the workshops). Workshops were used to involve the production team in the development of the model and to make the progression visible.

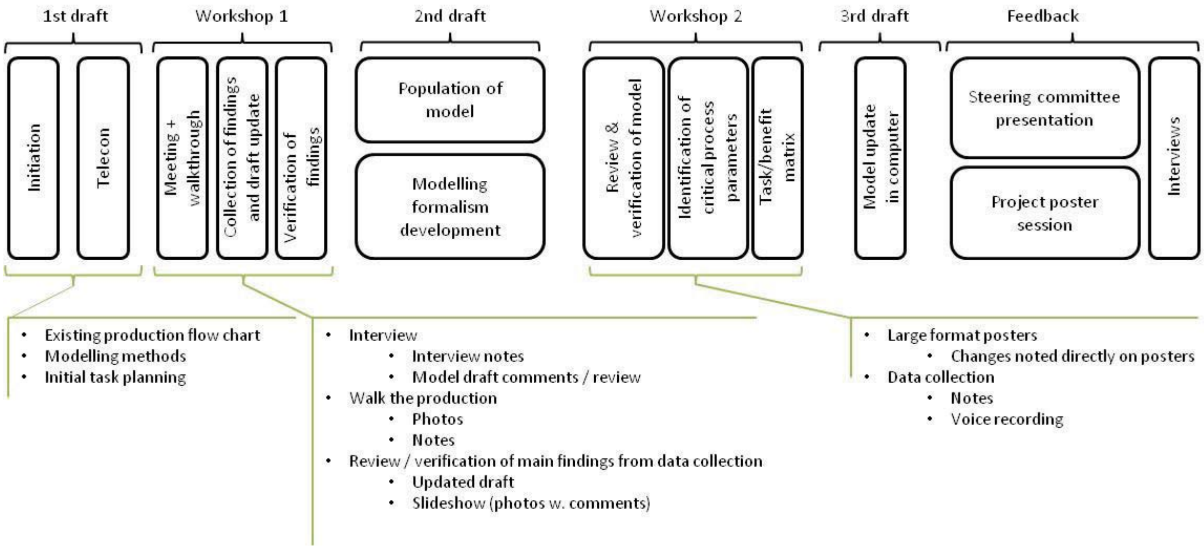


**Figure 1: The process followed in the case project, to develop the model.**

#### *3.1.1. Draft iterations*

The initial draft phase involved analysis of existing product process diagram, modelling methods in literature, alignment of expectations between researchers and production manager, and task planning. Subsequent draft phases comprised the main efforts in developing the modelling formalism and modelling elements, which were developed in parallel with population of the model and illustration activities.

#### *3.1.2. Workshop 1*

The aim of workshop 1 was to gain a detailed understanding of the production processes to be modelled. This workshop involved data collection activities. An interview was held with the production manager, where a draft model of the production formed a basis for discussions and was commented on by the production manager and researchers. During a walkthrough of the production with the production manager, photos and notes provided the main data collection method. Photo management software was used to produce a slideshow of the photos from the walkthrough with comments by the researchers on the processes depicted by the photos. The slideshow was used, along with an updated version of the draft model, to verify the findings during a review with the production manager.


**Figure 2: A large-format poster was used during workshops to facilitate active discussions and enable 'on-the-fly' changes to the model.**

#### *3.1.3. Workshop 2*

Workshop 2 involved, on behalf of the case company, the production manager, the project manager, and two process engineers. At the workshop four posters were utilized, one large format version of each production process to be modelled (past, current, future), and a production overview poster that included all modelling elements (see Section 3.2.1). The overview model was reviewed with the participants, during which comments and questions for discussion were welcomed and, if possible, noted directly onto the poster (Figure 2). Each of the process steps in the production was reviewed in detail to collect information on critical parameters for processes, accuracy of the model, and detail level. The workshop was concluded by reviewing a task-benefit matrix, showing how process improvement tasks within the project were linked to benefits in production performance or quality, and an update of the roadmap for production tasks.

#### *3.1.4. Feedback*

The production overview poster was presented by the production team to two recipient groups; the steering committee of the case project during a review and participants from other parts of the case project consortium. Feedback after the case was collected from the production manager and the project manager through interviews.

### 3.2. The developed model

The production overview, shown in Figure 3, was used to communicate the primary issues of the production development within the case project. The aim of the modelling task was to highlight the intended benefits of production equipment developments and investments, communicate the decisions to be made during the development of the pilot production, communicate the resulting output of key processes, identify where product characteristics are realized in the production process, and communicate the production process design to multiple recipients at different levels in the organization.

The main modeling was done in Microsoft® Visio®, as it was used for the previous flow modeling of pilot production in the company.

#### *3.2.1. General overview*

The production overview developed comprises four main sections.

*Vision* - A graph illustrating the vision of the increase in capacity communicates the aim of demonstrating production scalability. This is linked to (1) the material development progress and (2) the knowledge, and experience, regarding control over the production setup and processes.
*Production process* - Three production process models of the production, in initial (previous, 2011), present (current, 2013) and projected (future, 2015), respectively. Each production process model instance, in Figure 3 (2011, 2013, and 2015) shows a model of the production process at the respective time in the project. The details of the production process models are elaborated in section 3.2.2.
*Roadmap* - A roadmap shows the production process development tasks on a timeline, to illustrate the completed, current and ongoing tasks. The roadmap showed parallel development tasks aimed at improvements in all process steps.
*Benefit of improvements* - A task-benefit matrix shows what benefits or capabilities that completed production process development tasks will enable, in a number of dimensions, e.g. performance or product quality. The matrix showed that some benefits were realized by not only one task, but multiple tasks. Many of the tasks were also linked to multiple expected benefits.

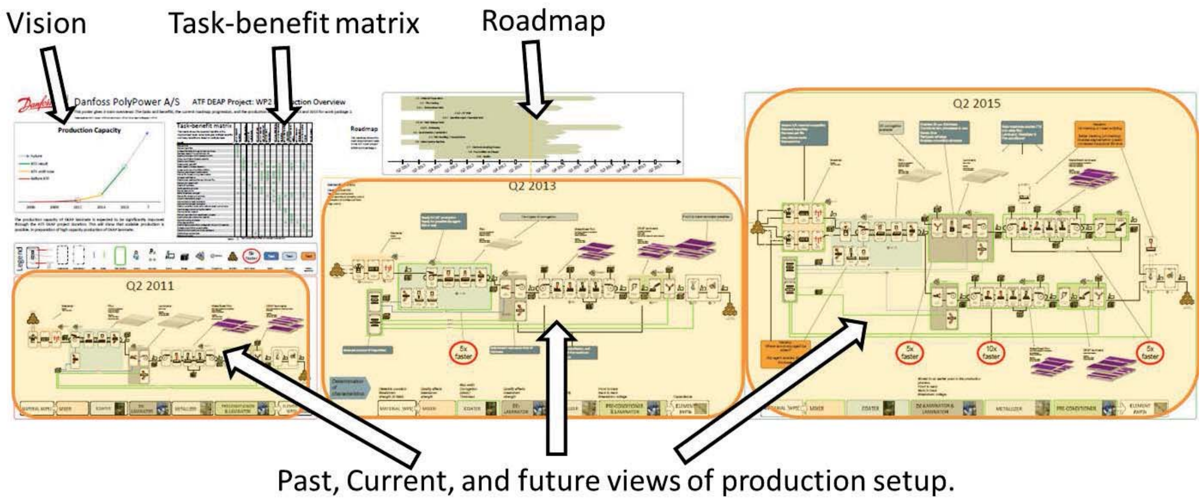


**Figure 3: Production overview poster from case project.**

*3.2.2. The production process models*

The production process models share the same modelling formalism. Figure 4 shows part of the production process model for 2013, along with selected modelling elements used in the modelling formalism to denote important issues. The production process models communicate the following aspects:
*The process flow* - Each of the process steps are illustrated by a rounded rectangle with a principle illustration to show the function of the process to aid communication to a wider audience. In addition, critical process parameters are noted for each process. The border of the rounded rectangle is used to indicate those cases where the process is implemented but not used or where a decision needs to be made for the particular process. The main difference, as opposed to the generic production flow model, is the focus on the processes and their critical parameters, their change over time, and their ability to create output variants, instead of identifying variant creation points within a defined product family.
*Storage and transport* - Storage and transport means between stations is illustrated, by graphical icons, to enable future analysis and optimizations of the production setup e.g. in relation to production scale-up.
*Main stations* - The main stations (machines) utilized in the film production are noted at the bottom of each model and as shaded backgrounds in the production process model. The colour of the shading links the two representations. The border of the rounded rectangle is used to indicate, those cases where the process is new.

*Resulting output* - The resulting output of each main station, in terms of film variants, is illustrated by CAD illustrations, highlighting where in the processes the variants are defined in the production.
*Process time* - Two types of information on processing time are communicated in the models. The processing time for a single batch of a certain size, is noted for each main workstation. An estimation of how many times faster a process will become with a planned upgrade from the roadmap is noted by a red circle for each workstation improved, for the particular production process model instance.
*Critical decisions* - Decisions to be made on workstations or processes are noted on the production process model. For each critical decision, the known alternatives and implications are noted concisely.
*Achieved characteristics* – At the bottom of each production setup view, the main stations of the production are modelled, with film characteristics noted. This links the achieved film characteristics to the main process steps, indicating where changes should occur in production to affect film characteristics.
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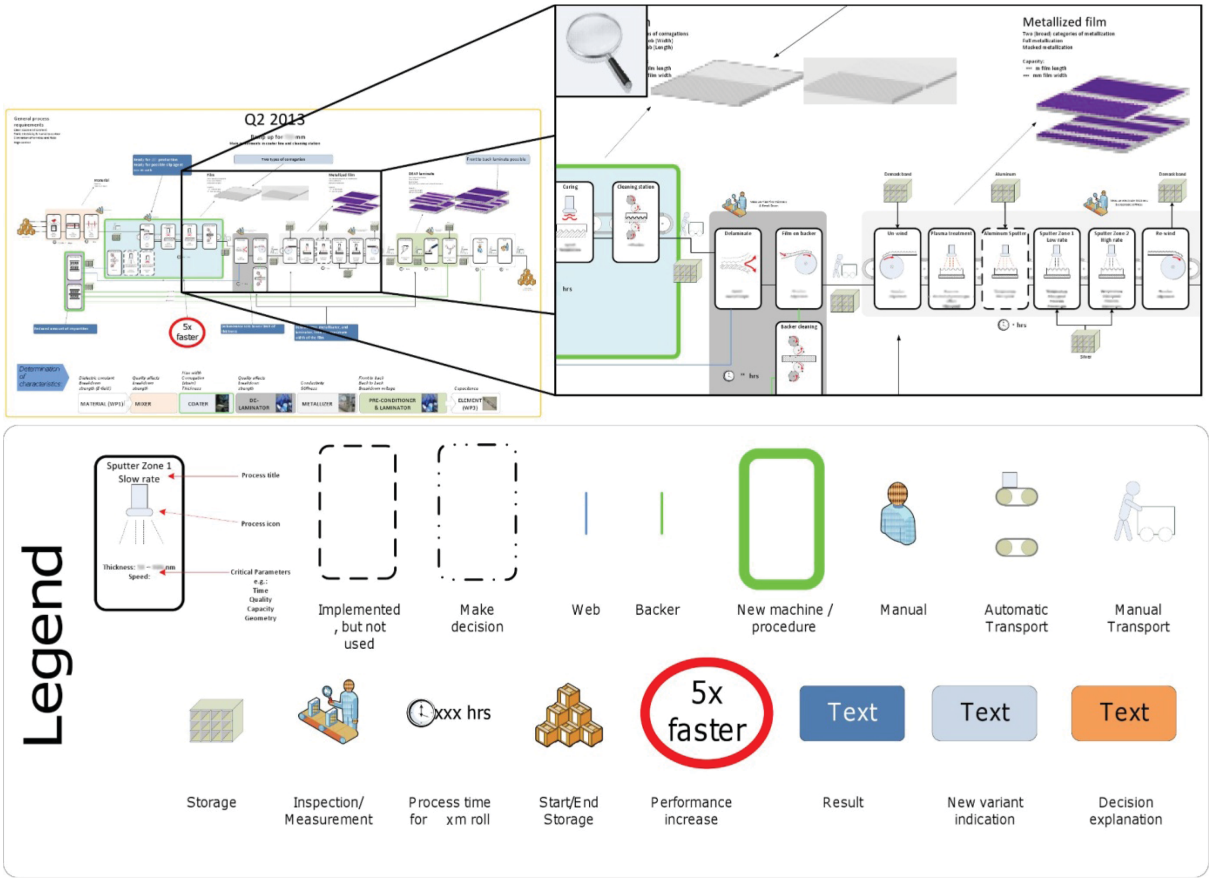


**Figure 4: Part of the production model of current production (top). Legend of the modelling formalism (bottom).**

## 4. Findings

The findings reported here stem mainly from the workshops, as observations, and from feedback interviews with the project manager and the production manager. Findings on the modelling process, as well as the use of the model for internal and external communication by the production team are treated in this section.

### 4.1. The modelling process

Using a commented slideshow presentation of photos to verify findings during workshop 1 was found to be a strong tool to create discussions and highlight the overall flow, and details, in a visual manner.

This reduced the amount of misconceptions after the first workshop, thus reducing the resources required to reach an accurate model of the production.
Bringing large-format print-outs, A0 or larger, of the model to workshops was found to be a crucial aspect in discussing the contents of the model, as well as noting comments, changes and suggestions 'on-the-fly'. The large format allowed the whole team to see details on the model and contribute to the session (see Figure 2). Bringing the production team together to discuss the models had a positive effect on bringing up issues regarding the production process development. The production team initiated discussions during workshop 2 to reflect on implications of new machinery, improvements of processes, and identification of critical process parameters.
The task-benefit matrix captured many of the links between intended benefits from the project and the production process development tasks in the project. The critical process parameters could be noted directly on the production process models, as well as implications of decisions on processing equipment or process flows.
Visualising the production process steps for the production team enabled them to 'show' the core of the process and how it is linked to the characteristics of the products; knowledge that was previously only found within the minds of the production team members. This link between the characteristics of production and production output (in this case the DEAP film) allowed the team to reason about future updates and predict what effect changes would have on the film. At the end of workshop 2 it was discussed by the team, whether it should be used for presentation of the production setup to an external vendor, as they saw it as a tool to provide the external vendor with a greater understanding of their production process.

### 4.2. Communication within the production team

The overview brought by the model, and the level of details in it, ensures that the production team is aware that they also need to keep 'this and that' in mind, when considering the production process. In interviews it was stated, that the visualisation, as opposed to standardized flow charts, made it easier to 'see' how a change in one process would affect further down the process flow. The model is therefore used whenever pros and cons of suggested process changes are discussed within the production team. The model effectively communicates what the activity is, what the process is, and what is critical. The link to what output variants are realized and what product characteristics are determined, by the process, shows what the purpose of the production process is.
The task-benefit matrix was intended to highlight what the different tasks/improvements would help on in the production, but when interviewed for feedback, the production manager stated that the team used the flow-models for discussions on improvements and the project manager stated that the full potential of the matrix was yet to be realised.

### 4.3. Communication outside the production team

The modelling task was considered to have fulfilled the goals of the steering committee, which initiated the task.
The model has been used to communicate the production process to parties outside the production team, both within the business unit and collaborators in the DNATF consortium. The production team has experienced the use of the model as beneficial for their ability to explain the process to external parties. Here, the graphical elements play a large role, according to the project manager, in explaining the production process to stakeholders that are not deeply involved with the production process. This was also viewed as an indicator that the model was a success by the project manager. That the production team could use the model, and explain it; especially that they could use it to explain to others what the production process, and its development, is all about.
The production manager has the intention of keeping the models updated for further use, as the production process models eased communication of the production process to parties both inside and outside of the production team.
For communication to persons outside the business unit, it was stated, that the overview may contain too detailed information, but for discussion within the production team the overview had a fitting level

of detail. It was, however, also noted by the production manager that it is easier to reduce the detail level for another recipient, than it is to increase the detail level.

## 5. Discussion and future work

There may be limitations to implementing the presented model in industry. The modelling formalism does not adhere directly to current practices in production models, frequently used by production managers and often integrated into PLM systems. Therefore, multiple models might need to be kept up to date in some companies, if this modelling was adopted. The present model, although based on models and approaches previously tested in industry, has only been implemented in an early stage production development, with a new product and new production. Its application within a more mature industrial setting has not been investigated.

In the EAP case, it was found through the interviews that the visual model presented the production team with a high amount of detail. This was reported to be of little matter, as the visual approach helped the team in the current phase of defining the production process. At a later stage, the model can be used as a base for a standardised flow chart, when the main process setup is in place, should a standard flow chart be preferred at that stage.The level of detail in the model was a result of the data collection and the extended generic production flow model formalism. As to the aim of having a model that allowed for communication with multiple recipients at different levels, the model has introduced an increase in detail when compared to the existing flow chart in the case. The aspect of communication internally in the production team and with externals revealed two different dimensions to be taken into account, an overview request driven by manager level, and detail request, driven by the expert team. This matter might be resolved in some cases by introducing layers, defined in the software, which allows details to be hidden for some recipients while using the same document. It is, however, an aspect that should be considered carefully, as adding layers may add detail as well as create confusion when deciding to what layers new changes shall apply. It is important to underline the fact that the main observations on the use of the model was made on printed versions of the model, not the virtual model. Further research on the use of the model in regards to updates, changes etc. would need to be investigated to evaluate the daily use of the model. As the developed model does not follow standard practises within companies to model production processes, finding employees that are comfortable with keeping the model updated may be an issue. However, the software used is readily available, relatively well known in industry, and often used for flow models in industry.

The model presented in this paper is not intended to work as a total definition of the production setup – it is intended to provide an overview of key factors to support discussions and decision-making, and its fitness to other purposes depends on its alignment with those purposes [Browning 2010]. The visual model has its strength in providing overview, details, and means for communication, in a technology pilot production. The applicability of this modelling formalism within established industrial production has not been investigated in this case.

The EAP film production is only a part of the production of an EAP transducer. Harlou [2006] emphasises the alignment between market, product and production architectures, as adapted in Figure 5. Within the DNATF project, the definition of transducer types is ongoing, supported by the Conceptual Product Platform (CPP) [Guðlaugsson et al. 2013], which looks into the market and product family views, and a system architecture modelling approach for support of the integration in test applications of the EAP, as illustrated in Figure 5. The work done with the CPP feeds into the definition of EAP transducer type definition. To support the transducer production, the proposed modelling approach can be further expanded, to support design decisions for the production of EAP transducers with links to the EAP transducer architecture from the CPP.

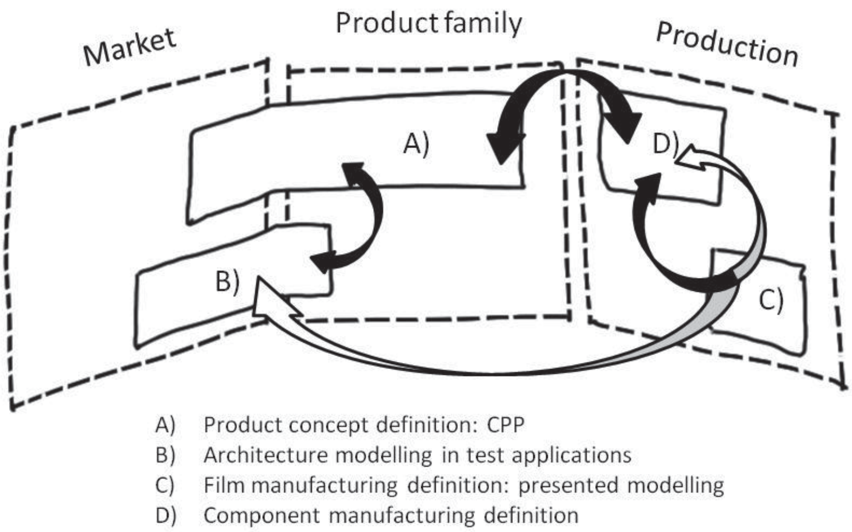


**Figure 5 – Linking market definition, concept definition and production definition. Black arrows represent content links and light arrows represent modelling formalism links. Market, product family, and production views adapted from Harlou [2006].**

## 6. Conclusion

A visual production model, based on the generic production flow has been developed for a pilot production in a technology development project of EAP film. The model has been well received by the production team and is being used both for internal communication and communication outside the team to illustrate the decisions, future changes, and the links to both an upcoming EAP component platform as well as the visual modelling of systems with which the EAP is being integrated. The visual model supported the management of tasks involved with production process development in the project, by fulfilling the following aims:

- Identify benefits of production equipment developments
- Communicate decisions during development of pilot production
- Communicate the resulting output after key processes
- Identify where in the production process, product characteristics are realised.
- Communicate the production process design to multiple recipients at different levels.

The method has given suggestions to the process of documenting the production in an early setup and the findings from the case project indicate that workshops on documenting the production process can help make the tacit knowledge of stakeholders explicit. The follow-up feedback stated, that the modelling was a help in the daily work in the production team.

### Acknowledgement

The presented work was carried out at the Technical University of Denmark and at Danfoss PolyPower. We would like to thank the Danish Advanced Technology Foundation for part funding of the research program at the Technical University of Denmark. We would also like to thank Danfoss PolyPower A/S for providing valuable input for the case description.

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# 10.5 PAPER E: FRONT END CONCEPTUAL PLATFORM MODELING


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**Abstract**

Platform thinking has been the subject of investigation and deployment in many projects in both academia and industry. Most contributions involve the restructuring of product programs, and only a few support front-end development of a new platform in parallel with technology development. This contribution deals with the development of product platforms in front-end projects and introduces a modeling tool: the Conceptual Product Platform model. State of the art within platform modeling forms the base of a modeling formalism for a Conceptual Product Platform model. The modeling formalism is explored through an example and applied in a case in which the Conceptual Product Platform model has supported the front-end development of a platform for an electro-active polymer technology. The case describes the contents of the model and how its application supported the development work in the project. The conclusion is that the Conceptual Product Platform model supports stakeholders in achieving an overview of the development tasks and communicating these across multidisciplinary development teams, as well as making decisions on the contents of the platform and providing a link between technical solutions and market requirements.

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# Front-end conceptual platform modeling

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**Abstract**

Platform thinking has been the subject of investigation and deployment in many projects in both academia and industry. Most contributions involve the restructuring of product programs, and only a few support front-end development of a new platform in parallel with technology development. This contribution deals with the development of product platforms in front-end projects and introduces a modeling tool: the Conceptual Product Platform model. State of the art within platform modeling forms the base of a modeling formalism for a Conceptual Product Platform model. The modeling formalism is explored through an example and applied in a case in which the Conceptual Product Platform model has supported the front-end development of a platform for an electro-active polymer technology. The case describes the contents of the model and how its application supported the development work in the project. The conclusion is that the Conceptual Product Platform model supports stakeholders in achieving an overview of the development tasks and communicating these across multidisciplinary development teams, as well as making decisions on the contents of the platform and providing a link between technical solutions and market requirements.

**Keywords**

Conceptual Product Platform, product platforms, technology platforms, multi-product development, platform development, platform modeling, front-end development

## Introduction

Industry faces an increasing demand for shorter product development time and better economies of scale. Previous studies have shown that considerable savings can be achieved through platform-based development. Black and Decker's redesign of the power tool product lines in the 1970s enabled them to lower production costs, reduce development time, and simplify the design of derivative products (Meyer and Lehnerd, 1997).

Reduced development time and R&D resource expenditure through platform-based design have also been shown for audio products (Harlou, 2006) and automation equipment (Sanchez and Collins, 2002). However, these cases deal with incremental innovation projects, that is, where existing product portfolios are rationalized or where new product portfolios are developed for well-known products and markets.

In radical innovation projects (Dewar and Dutton, 1986), there are often considerable uncertainties involved in the different facets of the development: market, technology, product, and production. These uncertainty factors may be even more confounded when the radical innovation project is run in a technology-push strategy. Earlier cases of technology-push efforts (Christensen, 1998) show that there are hurdles to be overcome to successfully commercialize a new technology, one of which is identifying the right markets and applications for the technology. In an ongoing technology-push effort aimed at commercializing a novel technology in a public–private partnership

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project (Hansen, 2013), measures are implemented to counteract technology-push difficulties. One such measure is aimed at reducing the effect of market, product, and production uncertainties by following a platform-based approach to enhance the potential to meet a wide range of market needs. This requires the ability to model and describe the contents of the platform, as it is developed in the front end of a radical innovation project, in a way that is able to deal with the uncertainties in market, product, and production.

While there are numerous examples in the literature of the application of platform-based development in mature product development environments, there are not many that deal with the front end of radical innovation. Description of support tools for front-end platform development for such cases is lacking.

This contribution explores the state of the art within product architecture and product family modeling, presents a Conceptual Product Platform (CPP) model as a tool to aid front-end product platform development, and describes a case where the tool has been applied.

This article is based on the work previously reported in Proceedings of the Electroactive Polymer Actuators and Devices 2013 conference (Guðlaugsson et al., 2013), which presented preliminary results. This article enhances the coverage of existing literature and the challenges of modeling a front-end product platform and presents a more mature description of the CPP model and its modeling formalism, as well as the contents of the model in an industrial case and the experiences of using the model in the case.

## State of the art

Through this state of the art, the following topics will be explored: product architectures and product architecture modeling, product family modeling, and knowledge sharing and creation to support product platform development.

### Product architecture

Product architecture is an explicitly defined perspective on the structure of a product. One take on an explicit definition of a product architecture includes "(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specifications of the interfaces among interacting physical components" (Ulrich, 1995: 420).

Commonality across product architectures, often achieved through modularization (Ulrich, 1995), is a characteristic that differentiates product family design from design of individual products and is linked to various benefits of alignment, such as economies of scale, increased product variety, reduced development time, and the enabling of parallel development tasks (Gershenson et al., 2003; Jiao and Tseng, 2000; Martin and Ishii, 2002; Prasad, 1996; Sanchez, 2004).

*Product architecture modeling.* Product architecture models aim to capture information on, and communicate a description of, the product architecture. They can be based on a variety of perspectives, some of which are covered below. Function models focus on the functionality provided by the products. Organs represent function carriers within products (Andreasen, 1980; Bruun and Mortensen, 2012; Ernst Eder, 2011). Function-means modeling uses a hierarchical tree to represent a breakdown of functions and design solutions (means) to those functions. Enhanced function-means models add interactions between elements in the tree to provide a more comprehensive product model (Schachinger and Johannesson, 2000). The Function–Behavior–State/Structure (FBS) model links the function, behavior, and structure of the product in order to describe *what* the product does, *how* the product does it, and *why* the product does what it does (Gero, 1990; Rosenman and Gero, 1994). Design structure matrices (DSMs) combine function modeling with matrices, depicting relations within the product. This enables the use of software algorithms to identify modules, which are especially beneficial in products with complex interactions (Eppinger and Browning, 2012; Hölttä and Salonen, 2003). Functional structure heuristics focus on flows in a function model of the product to identify modularization candidates in the product (Stone et al., 2000).

*Product family modeling.* The Product Family Master Plan (PFMP) models product families with an emphasis on including a multi-domain view, based on the Theory of Technical Systems and Domain Theory, which includes not only the product but also the market and production in the view of the product family (Andreasen and Mcaloone, 2008; Harlou, 2006; Hubka and Eder, 1988; Mortensen and Hvam, 2011). The PFMP model has been used in mature industries, and later developments of the PFMP mirror this as they add support to modeling production, commercial, organizational, and complexity cost issues (Kvist, 2009; Pedersen, 2010). Three-dimensional design structure matrix (DSM-3D) and DSM variety add dimensions to the DSMs to allow simultaneous analysis of multiple products. Product Family Heuristics use heuristic analysis of flows in the product family to aid modularization and support commonality, but none of these include market or production issues directly. The enhanced function-means model can provide a model of a platform with variants modeled through configurable components while relying on a hierarchical tree branching at each design solution alternative in the platform as well as comprehensive data on each design solution, constraint, function, and their interactions (Johannesson and Claesson, 2005).

### Knowledge sharing and learning to support platform development

Technology, defined here broadly as the ability to achieve an effect based on a scientific principle that requires in-depth knowledge about the scientific principle to apply and produce, is a central element in the front end of platform-based development and requires knowledge-seeking activities and sharing of the acquired knowledge between stakeholders. Three forms of knowledge, (1) know-how, (2) know-why, and (3) know-what, have been defined for knowledge architectures (Sanchez, 2000). Of these, know-why, answered through the research of new technologies and principles for future generations of a product, and know-what, answered by exploring new product concepts and architectures, are central to the front end of platform development.

Technology-intensive firms have developed technology platforms to support the reuse of technology and engineering knowledge within the organization, across both business units and product families (Nasiriyar and Jolly, 2007; Shapiro, 2006). Technology platforms are potentially of great importance for technology-intensive organizations, but there is little operational support to be found in the literature on how they can be applied and articulated in early-stage development. While the use of technology wikis to support platform development has been described in the literature (Levandowski et al., 2012), they are aimed at gathering, sharing, and integration of technological knowledge across a large organization at a higher level, not as a support tool for front-end development of product platforms.

### The challenges of modeling a front-end product platform

Commonality across variants within product families is of high relevance in product family development and may support economies of scale, shorter development time, and product variety. Product architecture modeling and, in particular, product family modeling provide support for sharing physical components across products in product families. Technology platforms, on the other hand, focus on the sharing of non-physical assets within organizations in support of reuse across product families. Products must, however, not be viewed in isolation—the purpose of the product is a central knowledge factor in product design.

Existing product family architecture models described above rely on rigid modeling formalisms and/or aim at optimizing design variables for modularization to support commonalities. However, existing models rely on detailed information on product design, which is difficult to fulfill in the uncertain environment at the front end of platform-based development. Technology platforms provide a support tool to share non-physical assets but lack support in how to model these non-physical assets during development and in relation to the purpose of the product.

What the literature does not cover is how to support front-end platform development within a dynamic solution space for an uncertain purpose while supporting commonality for future product families.

## The CPP

The tool described in this section aims at supporting front-end platform development, to model and communicate the foundation of the product portfolio of the organization, within a dynamic environment with uncertainties on many levels.

The tool builds upon the previous work discussed in section "State of the art," especially the PFMP (Harlou, 2006). While these existing platform models focus on the product side of platforms, extending into part and process domains, the CPP aims to create an overview at a higher level of abstraction. Existing platform models provide support to model product families under the following conditions: (1) the organization has in-depth knowledge of the market, (2) existing product portfolios to base product development on, and (3) existing production processes for their product families. The CPP aims to support development in the rare case when the organization lacks (1) a clearly defined market or knowledge of the market, (2) existing products to base a platform on, and (3) matured production processes.

At this level of abstraction, the product concept structure, principal solutions, and key interfaces, in future or existing products, are modeled visually. An overview is thus obtained to communicate both the capabilities and developed solutions that exist within an organization and can be exploited to produce technology-based products. Through a CPP model, an organization should be able to describe what the market requires, in terms of technical solutions or technological capability, and what the organization is able to provide, or needs to acquire the capability of providing. While detailed part design lies outside the scope of the CPP, it allows for standardization of principal solutions and technology use within a product portfolio, increasing the probability of commonality in production processes and achieving a greater value from technological know-how within the organization.

The CPP is envisioned to be able to provide a foundation for multiple product platforms, catering for diverse application requirements. While the product platforms may not be able to provide significant sharing of common parts and components, they can be based on the same technologies, scaling principles, and/or production processes.

## Modeling formalism

This section describes the modeling elements of a tool developed to model a CPP, as shown in Figure 1. These modeling elements can be used to summarize, collect, and identify information on what is required from the platform, what the platform can provide, and what the platform needs to contain to be able to compete in the market. Therefore, each of the modeling elements should be viewed as input to the neighboring modeling elements.

The *application requirements* are a list of requirements for applications, market segments, and use scenarios, which can clarify what needs to be taken into account when developing the CPP (Marion and Simpson, 2006). The requirements are statements that describe the needs and expectations of the stakeholders in the intended market that need to be fulfilled in order for the product to be accepted within the particular application (Holt et al., 2012). They may represent requirements fulfilled by competing products, or incumbents in the case of new market entry, or be based on explorative market research or collaboration with potential customers.

*Application concepts* illustrate particular solutions, in which product concepts fulfill application requirements. These may represent conceptual use scenarios that need to be supported or systems that the product concepts must become part of or integrated into.

The *product specifications* state the needed performance of the product in order for the product to fulfill the requirements of a particular application within the context of a particular application concept. They represent key specifications that influence the choice of organ alternatives or highlight where the CPP currently lacks capabilities.

*Product concepts* illustrate products that are, or may be, achievable by combining organ alternatives from the CPP. The concepts are illustrated along with the particular organ alternatives that provide the required functionality.

An *organ* provides an internal function within a product and is also known as a function carrier or functional unit (Hubka and Eder, 1988). It produces an effect and in turn provides an internal function, such as when the friction of two plates held together by a bolt provides the function of connecting the two plates (Mortensen, 1999). The organ diagram, based on the generic organ diagram (Harlou, 2006), depicts the generic architecture of the product concepts through the organization of organs within the product concepts. Some organs may not be needed in all products (or product types); they may provide added value or only be needed in some applications.

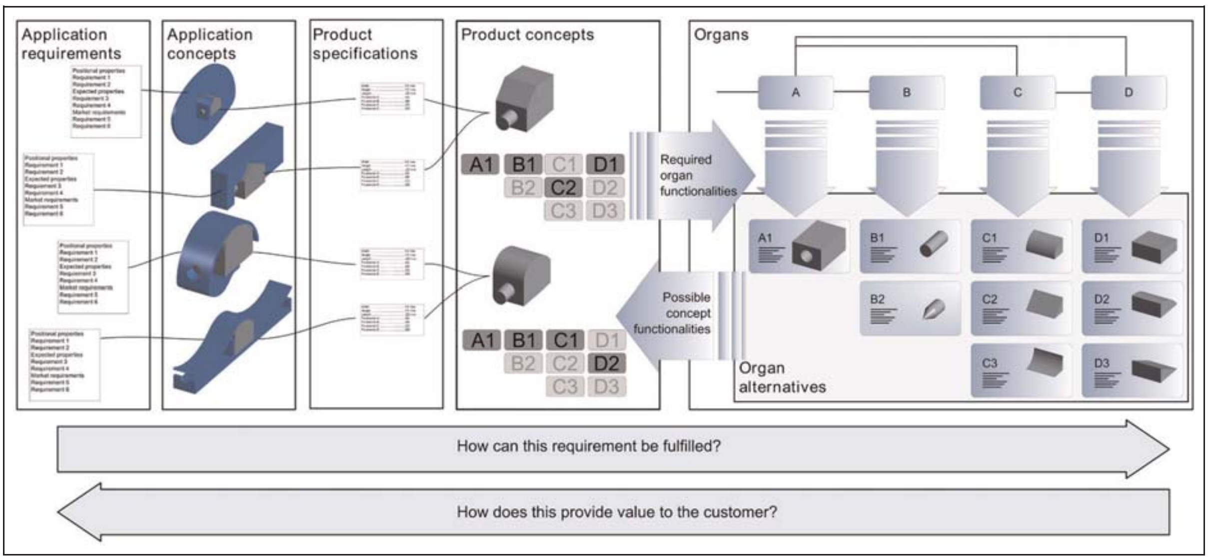


**Figure 1.** An overview of the modeling elements in the Conceptual Product Platform.

*Organ alternatives* represent alternative means of acquiring the internal function to be provided by the organ. Each alternative may perform differently on a variety of relevant parameters, which serve as rationale for the organ alternative's inclusion in the platform: performance or feature levels, trade-off curves, technology "s-curves" (Nieto et al., 1998), technology readiness levels (Mankins, 1995), or technical capabilities of the organization.

*Reading the CPP model.* A core element in the CPP model is the horizontal reading order, illustrated in Figure 1. When read from left to right, the CPP aims to show how an application requirement can be met through the platform contents, while a right to left reading order aims to show how platform elements can provide value to the customer. The placement of the applications to the extreme left is chosen to indicate that the contents of the CPP should arise as a consequence of application requirements. The contents of the CPP can be iteratively refined through this reading order—when the contents fulfill the application requirements and include only those organ alternatives that provide value to the applications, the CPP may be considered saturated. The visual format of the model is intended to support communication of its contents to both internal and external stakeholders.

## Electro-active polymer CPP case

The tool presented in the previous section was developed in a case study, as part of a collaborative technology platform project in Denmark. The research approach is based on action research (Checkland and Holwell, 1998), with primary data collection methods being observation, field notes, interviews, and documents from the case project. The project, initiated in June 2011, aims to mature an electro-active polymer (EAP) technology through a collaborative consortium of multiple organizations from industry and academia. The project is partly funded by the Danish National Advanced Technology Foundation (DNATF). This article focuses on the application of the CPP to support the development of a platform for the mechanical construction of EAP transducers, which is intended to form the foundation of the future products of Danfoss PolyPower (DPP). DPP has 17 employees but is a fully owned subsidiary of Danfoss A/S with around 23,000 employees. The DPP EAP is a dielectric silicone film material (EAP film) with a corrugated surface on which a metal electrode is deposited. The corrugated EAP film is laminated to produce an anisotropic EAP film, which expands in a direction perpendicular to the corrugation when high voltage is applied (Tryson et al., 2009).

### The CPP model from the case project

A model of the CPP was gradually filled in as the development work progressed. Figure 2 shows a late incarnation of an overview poster used in the project work, in which hand sketches illustrate the contents in the overview. The model was implemented using Microsoft® Visio®, with graphs prepared in Microsoft® Excel®. The contents of the CPP model in the EAP case are described in this section.

The application requirements comprise the main identified requirements, based on interviews with application experts within the DNATF project. Estimated application requirements for additional applications, based on explorative market research, supplement those from within the DNATF project but are considered more uncertain. For each application, the requirements are categorized based on the Kano (1995) model to highlight which parameters are most important.

The application concepts comprise sketches of EAP transducers applied to fulfill the particular application requirements. They represent early-stage ideas to provide inspiration for the development of the platform elements and what the platform may need to be prepared for. The strategy for DPP is to develop and market business-to-business (B2B) products so that the sketches depict EAP transducers as a subcomponent in a customer system.

Transducer specifications list estimated values of the primary identifiable parameters of a transducer for the particular applications. Primary actuator parameters, such as force, stroke, and frequency, are most frequent, but further specifications, such as lifetime, size, strain, and temperature ranges, are included if deemed crucial for the particular application. The precision—mirroring the access to data on application requirements—ranges from particular specifications, through quantifiable ranges, to relative descriptions such as high or low.

Product concepts are represented by sketches of transducer concepts. They illustrate the design of various EAP transducer concepts, along with the organ alternatives they comprise, linked to application requirements through the transducer specifications. The concepts in Figure 2 are the most promising concepts developed within the project and provide a basis for deciding which organ alternatives are necessary to fulfill the application requirements.

Figure 3 shows two versions of an organ diagram, showing the same organs, which are used in the project. One is based directly on the generic organ diagram (Harlou, 2006), and the other has a more direct link to the structure of the EAP transducers, illustrated by the linear actuation Axial 1 in Figure 3. In the latter, interfaces are implicitly represented by either adjacency of the boxes or the box-within-a-box representation in the

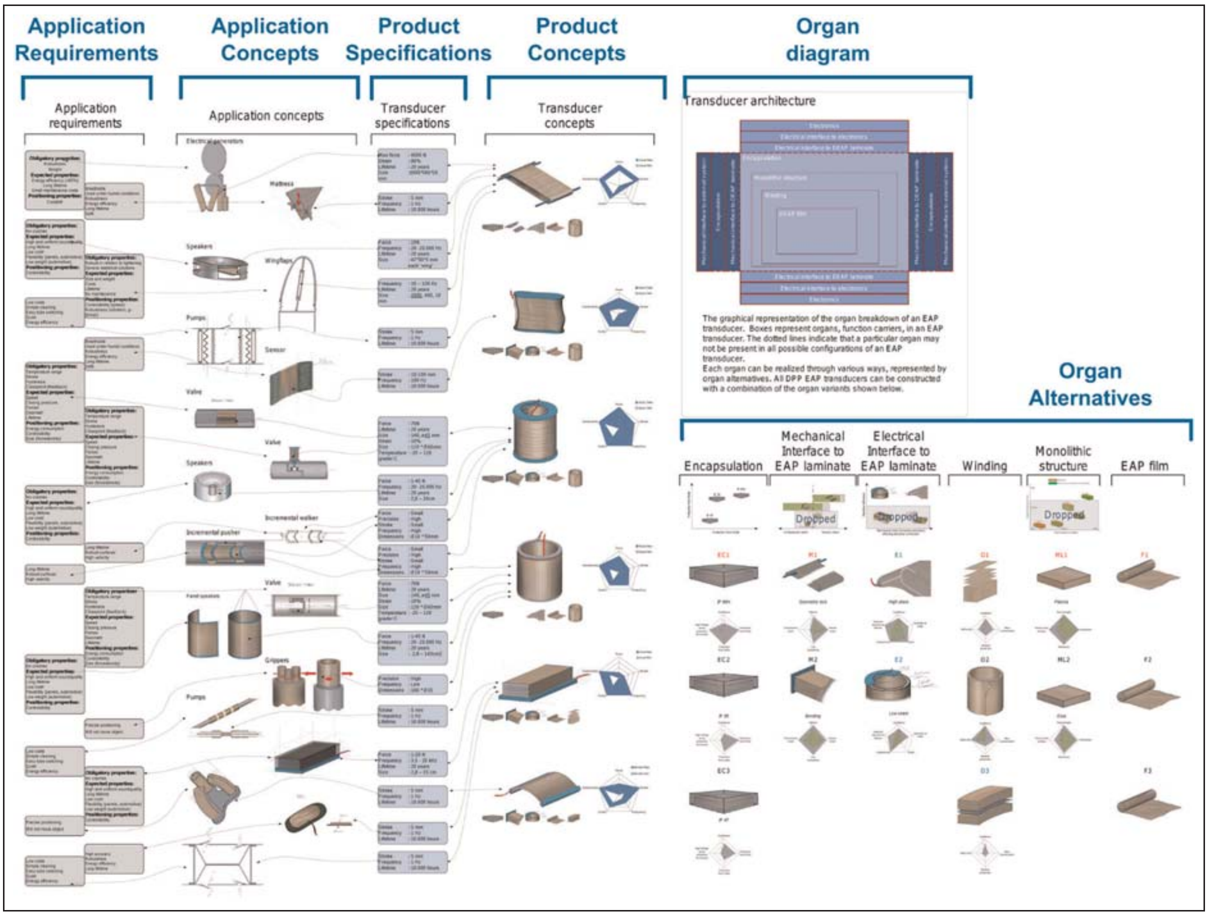


**Figure 2.** The CPP model from the case project shows an overview of the development tasks.
CPP: Conceptual Product Platform; DPP: Danfoss PolyPower; EAP: electro-active polymer.

central part of the figure. In this version, the hierarchy in the central part of the figure reflects the construction of the EAP transducers and can assist in ensuring coherence between process and product architectures (Sanchez, 2000). Both versions are used in parallel to ensure that interfaces are explicitly defined.

Organ alternatives are listed for six organs from the organ diagram: encapsulation, mechanical interface to EAP laminate, electrical interface to EAP laminate, winding, monolithic structure, and EAP film. The mechanical interface to external systems, electrical interface to electronics, and electronics were considered outside the scope of the work covered in this article. The organ alternatives represent technologically or conceptually different means to achieve the required functionality of the particular organ. They are derived from application requirements through transducer concepts but are decoupled from individual applications. The organ alternatives differ in their intended performance, providing a broader solution space than if a single alternative was used. This provides the rationale for inclusion within the platform and R&D resource expenditure. The performance of each organ alternative, either intended or verified performance, is illustrated graphically in the CPP. Comparison graphs for selected organs include organ alternatives that have been dropped as the feasibility of better performing organ alternatives has been verified.

*Supporting documentation.* In practice, further documentation of findings related to the CPP was maintained to a more detailed degree than was feasible to do on the CPP model directly. The detailed findings were therefore documented in reports that were directly linked to elements in the CPP. These documents allow sharing of knowledge within the project through a central repository used in the project and accessible to all project participants as an ad hoc version of a technology wiki approach (Levandowski et al., 2012).

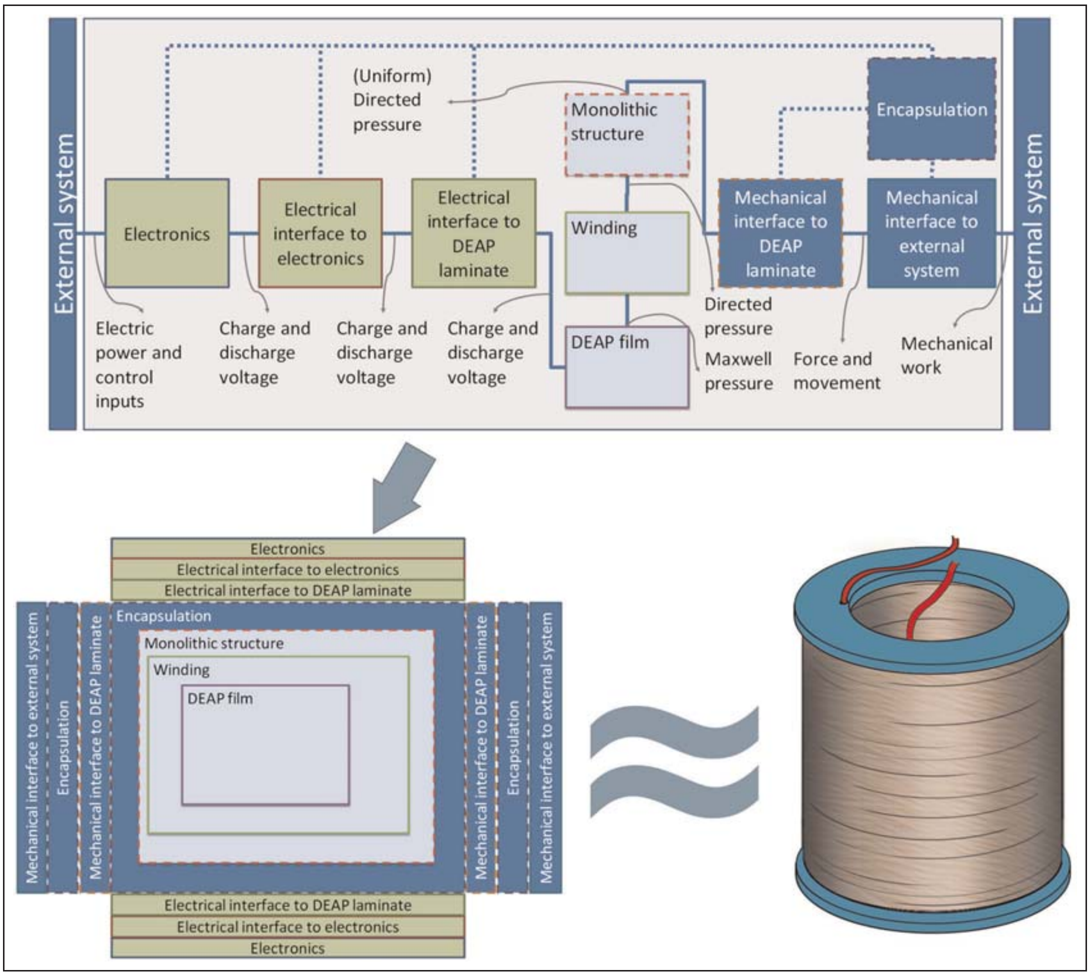


**Figure 3.** A generic organ diagram (top) for an EAP transducer and an alternative visualization of an organ diagram (bottom left), which is a graphic representation of an EAP transducer from the case project. An EAP linear actuator of type Axial 1 is shown for comparison (bottom right).
EAP: electro-active polymer; DEAP: dielectric electro-active polymer.

## *Experiences from using the tool in the EAP case*

The CPP model, in the form of a large format poster, was extensively used during meetings as a communication tool, both as an overview and during more focused discussions on the tasks regarding specific organs and organ alternatives. It provided participants with a reminder of the contents of other tasks, while these were being discussed, and acted as a tool to ensure that all attendees were aligned in their perception of particular organ alternatives, application requirements, or other facets of the development work depicted in the CPP model. The physical format of the CPP model allowed participants to add to this model during meetings, or to mark and change existing information, based on input acquired during the meeting. The CPP model was then electronically updated accordingly after the meeting.

Concept evaluation and elimination were performed using the CPP. Multiple concepts in the CPP were able to fulfill the same application requirements, and concept reduction was based on their ability to fulfill multiple application requirements and their sharing of organ alternatives. This allowed the technical solution space to be reduced, without impacting the platform's ability to fulfill application requirements, and ensured that technical solutions were decoupled from individual applications as the uncertainties around EAP transducer applications were still significant.

The CPP model has also been used as a communication tool toward parties outside of the team working on the platform. The recipients can be split into four main groups: participants from platform development work package, project participants from other work packages, members of the steering committee, and customers visiting DPP. Table 1 shows an overview of the

**Table 1.** The CPP model has been used as a communication tool toward the four groups of recipients.

| | Communication form | Utilization dimension |
|---|---|---|
| Participants from platform development work package | A poster showing that the CPP model has been hung on the wall during meetings with other work packages | Track performance goals for organ alternatives<br>Link development tasks within the platform to application context and to other work packages<br>Provide a platform perspective during discussions on tasks within platform development<br>Decide focus of organ alternative development tasks based on design rationale<br>Evaluate the contribution of organ alternatives to the platform to make decisions on which development tasks to continue and discontinue |
| Participants from other work packages | A poster showing that the CPP model has been presented during meetings with other work packages and hung on the wall during meetings with other work packages | Present platform contents and capabilities<br>Link development work in the other work packages to the platform development to identify performance factors for platform<br>Communicate platform capabilities during concept development for key applications |
| Steering committee | Parts of the CPP model have been presented in presentations at steering committee meetings to provide an update of the progress in the development of the project | Prioritize focus areas and resources within the DNATF DEAP project<br>Evaluate platform potential and platform development work with focus on platform capabilities and feasibility of development work |
| Customers visiting DPP offices | The CPP model has been presented to visitors to DPP offices, both customers and potential customers | Present platform contents and capabilities<br>Discuss potential platform solutions for customer's application |

CPP: Conceptual Product Platform; DNATF: Danish National Advanced Technology Foundation; DEAP: dielectric electro-active polymer; DPP: Danfoss PolyPower.

four recipient groups, the form of communication, and the reception of the communication.

The extensive use of hand-sketched illustrations to communicate product and application concepts, organ alternatives, and technical principles was well received by the project team. Some project members were not well acquainted to using hand sketches as a communication tool, but have expressed their appreciation of the sketches' ability to communicate ideas while indicating that the ideas are not fully developed.

The generic organ diagram was not well received by the team members. The team members felt it was too abstract and did not represent their idea of an EAP transducer. The alternative illustration that includes all the same organs, but has a more direct link to the EAP transducers, was received better by the team members; they could identify the revised graphic as a representation of an EAP transducer, and discussions about the diagram could focus on the tasks at hand, rather than the formatting of the diagram.

## Conclusion

The main contribution of this work is the CPP model. The CPP model has provided operational support to mechanical platform development within a real-life industrial technology–push project aimed at maturing and commercializing a novel technology. The CPP has supported the development through the identification and organization of organ alternatives, evaluation and selection of product concepts based on application requirements, as well as providing an overview of the platform, its contents, and its links to the intended applications.

By providing an overview of organ alternatives, it has supported the communication of development tasks and their status and decisions on the continuation of development tasks. The link to the intended applications provided the technical development team with a context for what was required of the technical solutions being developed and a measure of what provides value to the intended applications—providing a decision base for platform contents. The CPP model has furthermore proved a valuable communication tool toward the development team, project collaborators, management stakeholders, and potential customers.

The case study has shown that the use of a visual model in a physical medium that could be updated during meetings helped to ensure that the model showed the current state at all times and that relevant stakeholders were aligned in their perceptions regarding the development tasks.

Further work that could be relevant to this research includes applying the CPP model on a broader scale, for example, by including other technical domains such as electronics or in cases with other participants.

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## Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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## 10.6 PAPER F: MODELLING PRODUCTION ARCHITECTURES IN THE EARLY PHASES OF PRODUCT DEVELOPMENT

Submitted to a peer reviewed Journal, 2015

Authors: Guðlaugsson, T. V., Ravn, P. M., Mortensen, N. H., Hvam, L.

**Abstract**
This article suggests a framework for modeling a Production Architecture (PA) in the early phases of product development. The challenge in these phases is that the products to be produced are not completely defined and yet decisions need to be made early in the process on what production capabilities are needed and appropriate to enable determination of obtainable product quality.

In order to meet this challenge a modeling framework is suggested, one that clarifies which product and production features are known at a specific time of the project and which features will be worked on – leading to an improved basis for prioritizing activities. Requirements for the framework are presented and literature on production and system models is reviewed. The PA modeling framework is founded on approaches in literature and adjusted to fit an early phase of development. The PA models capture and describe the structure, capabilities and expansions of the PA.

The framework is tested in a case study. The results indicate that the modeling process facilitates identification of critical factors of the PA, that the PA models capture and describe the structure, capabilities, and expansions of a PA, and that the PA models can facilitate dialogue across stakeholder groups.

# Modeling production architectures in the early phases of product development

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**ABSTRACT**

This article suggests a framework for modeling a Production Architecture (PA) in the early phases of product development. The challenge in these phases is that the products to be produced are not completely defined and yet decisions need to be made early in the process on what investments are needed and appropriate to enable determination of obtainable product quality.

In order to meet this challenge, it is suggested to adopt a visual modeling framework that clarifies which product and production features are known at a specific time of the project and which features will be worked on—leading to an improved basis for prioritizing activities in the project. Requirements for the contents of the framework are presented and literature on production and system models is reviewed. The PA modeling framework is founded on methods and approaches in literature and adjusted to fit the modeling requirements of a PA at an early phase of development. The PA models capture and describe the structure, capabilities and expansions of the PA under development.

The PA modeling framework is tested in a case study and the results indicate that the modeling process facilitates identification of critical factors of the PA, that the PA models capture and describe the structure, capabilities, and expansions of a PA under development, and that the PA models can facilitate dialogue on the PA between heterogeneous stakeholder groups.

***Keywords: Production modeling, system modeling, production architecture, production modeling, product architecture, concurrent engineering.***

## 1 Introduction

When developing a production architecture (PA), methods exist for describing the product architecture (1,2), however, when developing a product architecture in parallel with developing new products during technology development, the definition of the products and the production system that existing approaches in literature rely on, are not complete.

To support the development of the production system despite the incomplete definition of both the products and the production system, two approaches may be valuable: (i) Graphically modelling the incompletely defined Production Architecture (PA)(3). (ii) Developing the PA concurrently with the development of the product architecture that will define the products to be produced by the PA (4–6). To accomplish this, however, we need a modelling approach which clearly shows which parts of the product and production architecture have been defined and stabilized, and which parts are still under development.

The structure of the production architecture comprises the processing equipment, factory layout, level of automation, organization of the production, planning methods etc. (7). The production architecture is derived from the production task, which outlines the functional requirements to the production based on the company's strategy, the products to be manufactured and other external conditions crucial for determining the structure of the production architecture

Concurrent development of product architecture and a PA during technology development is illustrated in Figure 1. The production task definition (7) in the early phases includes external factors leading to crucial functional requirements to the production system. In technology development—covering Technology Readiness Levels 1-5 (8)—the product design, product performance, required and obtainable product quality, production processes, and production technologies are still unknown and subjects for consideration by the development team.

To facilitate the analysis and synthesis in the development project, we need to make the requirements for the production system visual—gradually—as the products are being designed. The design of the PA requires gradual determination of performance criteria such as cost, required and obtainable product quality, return on investment, volume, scalability of production capacity and product flexibility (7). This research focuses on modelling a PA to support PA development and implementation decisions during an early phase of development.

### 1.1 Structure of the paper

The remainder of the paper is structured as follows. First the requirements for the model are investigated in section 1.2, by establishing what needs to be clarified during development of the PA. In section 2, existing system models and production models in literature are reviewed and compared to the requirements for an early phase PA model. In section 3, the research aim and method presents the background for the research and how it was performed. Section 4 describes the contents of the PA model and its links to relevant literature. Section 5 describes a case where the PA modelling framework was applied and the results from implementing the models in the case. Section 6 presents a discussion on the suggested modelling framework based on theory and findings from the case study. Section 7 presents the conclusions from this research.

### 1.2 Requirements for a Production Architecture model

A clarification of what modelling elements a model of a PA should contain is needed by identifying relevant production system design factors. A literature search was performed in Google® Scholar® to identify relevant factors using combinations of the search terms “manufacturing”, “manufacturing system”, “production”, “production system”, “technology”, “process”, “design”, “development”, “selection”, and “architecture”. The titles of search results were used to identify potentially relevant papers, whose abstracts were read to identify relevant papers. To support this identification a list of relevant factors for production system design from literature has been used as a reference (7). The focus within this work is on identifying factors relevant to modelling a production system under development; to identify what it is, what can it do, and what it should be able to do in the planned future?

The following is a categorized list of relevant factors that forms the requirements of what should be represented in a PA model during technology development:

### 1.2.1 Structural elements of a PA (what is it?)

- The constituent elements, such as sub-systems, the equipment and workstations (1), and structure, where the structure is the organization of the physical elements and their relations (9).
- Links from a production system's elements and functions to elements of the product architecture through dispositional effects (10).
- Indication of the choice of production technology; a key determinant for achievable functionality of the production system and investments required to implement the production system (7,11).

### 1.2.2 Functional elements of a PA (what can it do?)

- Product flexibility, as it is the capability to produce new product variants economically and quickly (12,13), which is necessary when the product architecture description is not complete—the aim should be to obtain the right flexibility (14,15).
- Volume flexibility, as it is the range of production volume within which the production system can profitably produce products and important in new product introduction (16)
- Processing and setup times, batch sizes, and partially produced goods, as these greatly affect the production system performance (1,17,18).
- Product differentiation points, as these affect product design as well as product and volume flexibility (19).
- Indication of obtainable quality, as quality is generally prioritized over flexibility and should be considered during production system development (20).

### 1.2.3 Expansions to the PA (what should it be able to do in the future?)

- Production volume scaling, as moving from a laboratory setting to industrial production scale can require rigorous experiments on industrial production equipment to identify performance parameters and improve obtainable quality (21,22).
- Capabilities, as these can be expanded upon to enable delayed investment for capabilities that are not needed until later on—interfaces between sub-systems are central to facilitating capability expansion (12).

Some of the most critical elements of the production system are the required and obtainable product quality, flexibility for volume and product changes, cost and productivity (7). As a PA can be assumed to be incompletely defined during an early phase, a complete model of all these elements may not be achievable or prudent. For example, process technology and scaling principles are highly relevant in the early phases, while batch sizes and setup times are of greater relevance in later phases.

# 2 Literature review

The modelling of a PA during technology development relates primarily to three facets of the PA: Its structure—to identify processes, critical equipment, and process flow; its capabilities—to determine what the PA is capable of producing; and its expansions—to identify planned and implemented improvements to the PA's capabilities.

## 2.1 Modelling the structure of the PA

System modelling has been applied to model the structure of systems as comprising functions and structure, where the structure is the organization of the physical elements and their relations (9). Production systems can be seen and modelled as large systems (23,24), where the constitutive modelling elements are the individual processing equipment and workstations (24). The relations between structural elements in the production system primarily take the form of material and tool handling.

Flow models are a common way of modelling the structure of a production system and show the processes of the production system and routing or flow between processes (25). The detail in process flow models varies, from illustrating only the flow between processes to more detailed models identifying product variant creation, utilizing standardized graphic notations, IDEF or UML modelling formalisms, and links to process simulations and routing optimization algorithms (26–30).

Layout models are primarily used to determine an optimal layout of production equipment within the production facilities (18,31). They can span entire factories or be focused on a single workstation (3) and are focused on the physical layout and relations between equipment.

### 2.2 Modelling the capabilities of the PA

Few models depict the capabilities of a production system directly. Some variants of flow models include details such as the product variant differentiation points, which provides indication of what product variants can be produced by the production system (30). Layout models may also contain information on capabilities, such as capacity, process, and cycle time (3). Value Stream Maps (VSM) depict the capabilities of the whole value chain, mostly in the form of performance parameters (e.g. processing and cycle times) and may contain similar capability information as layout models (32,33).

Capability modelling can utilize graphical elements such as illustrations of product variants at differentiation points and bar graphs for production volume capacity, e.g. in the Generic Production Flow (GPF) (30), or as numerical data on performance parameters (3,34).

Linking the products to the PA indicates capabilities and has been done for mature product families using linked models for Bill-of-Materials and for product and process platforms (2,35). These links are utilized in the production process planning approach, but as they are based on optimization using extensive historical data on products and processes (36), this approach is not fitting for direct implementation during technology development. An integrated model can be used to model the production system with the WIP as an integrated part of the model, but this requires multiple models to model the different states of manufacture and the detailed interactions between the parts and the production equipment (4).

### 2.3 Modelling expansions to the PA

In literature quantitative models that compare production technologies on a cost basis with regards to demand and capacity (37), that include flexibility and uncertainty (38) and that consider the optimal choice of production technology based on investments, costs, capacity capabilities and demand (39). But these quantitative approaches require input data in the form of demand and cost estimates and lack focus on modelling the constitutive aspect of expansions—how expansions affect not only capabilities but also structural aspects of the expansion plans. The expansions to a PA can be modelled also multiple layout diagrams to show alternative configurations of a workstation, including performance data on each alternative (3), which enables modelling of both structural and capability expansions using multiple uniform models. A multiple model approach is also used with VSM's, where two maps are generally generated; one for the current state and one for the future, improved, state (33).

### 2.4 Summary of literature review

A variety of approaches to modelling the production system from a diverse set of perspectives exist in literature. Structural models facilitate determination and communication of the structure of the production system, but generally lack information on capabilities and expansions. Existing models that include capabilities are focused on mature production systems producing well defined product families. While many capabilities of the production system are modelled in existing models, the modelling is either limited to a few performance parameters or relies on extensive data sets on products and processes to support optimization of the production system. Extensive numerical data sets are unavailable during technology development and therefore quantitative expansion modelling is not suitable. Modelling expansions to the production system through the use of multiple models showing the differences between 'current' and 'future' states have been successfully applied in industry. However, models have not been found that combine a model of the structure and capabilities of the production system with expansions modelling during technology development.

## 3 Research aim and method

This research focuses on developing a modelling framework that captures and facilitates communication of critical PA parameters during technology development. In light of uncertainties regarding both the product and production architectures during technology development, the framework must facilitate a gradual clarification of critical PA parameters as development progresses. The aim is both to develop and test a modelling framework that supports firms in identifying critical production system development parameters and decisions during technology development. PA development and parameters need to be clarified across stakeholder groups, so the framework should suit multiple audiences.

## 3.1 Research method

The modelling framework was developed on the basis of literature, experience, and feedback from practitioners. The literature foundation was formed by a literature review of theories on systems theories, integrated product development, production system design, production modelling, manufacturing flexibility, process platforms, product architectures, and product family development. The researchers drew on experience from research within product family development, production modelling within product development, and integrated product development from the research. Industrial practitioners provided feedback through testing, as well as providing ideas based on best practices and information on requirements for the modelling framework.

### 3.1.1 Testing the modelling framework

The modelling framework was tested in industry to evaluate whether it would be practical to use in industry, whether critical parameters and decisions would be identified through use of the modelling framework, and whether communication of parameters and decisions to heterogeneous stakeholder groups would be facilitated the modelling framework.

The researchers' role was to perform the modelling task with input from interviews and workshops with practitioners, along with existing documents describing the production system. Interviews with multiple stakeholders were used to evaluate the use of the models—supplemented by direct observation.

# 4 A framework for modelling the Production Architecture

The modelling elements of the PA modelling framework, illustrated in a generic format in Figure 2, provide information on the PA from the three distinct perspectives. The *structure* of the PA describes what it is by modelling two levels; (i) main stations, processes, flows, parts, and tools, and (ii) critical equipment and the definition of product characteristics. The *capabilities* of the PA describe what it can do through modelling the product variants produced, the product flexibility, volume flexibility for each main station. The *expansion* plans describe changes to the structure and capabilities of the PA that are expected to be realized through investments or other decisions made during the development of the PA.

## 4.1 Structure

The structure of the PA is modelled at two levels—a process level and an equipment level—to describe the structure of the PA, the production technology choices made, and the dispositional effects between the PA and the product architecture. The processes are modelled on the basis of function modelling and the GPF (30,40) to describe the processes and the relations between them in the form of interfaces. The equipment level describes critical equipment and workstations and the critical product characteristics that are defined at each of them.

The process level includes individual processes, groups of interlinked processes modelled as main stations, stock, and material handling. Each process is described with a symbol and a note of critical process parameters that are central to increasing the capabilities of the PA or determining obtainable product quality. The interfaces between processes describe the flow of parts, work pieces, and tools.

The equipment level description emphasizes the dispositional relationship between the PA and the product architecture (10). To achieve changes in product characteristics, equipment linked to the definition of the particular product characteristics may need to be updated or changed—and changes to the equipment may affect the product characteristics linked to the equipment.

## 4.2 Capability

The capabilities of the PA represent the functional aspects of the PA. They are modelled with an emphasis on product variant creation  and system level manufacturing flexibility, which includes process, routing, product and volume flexibilities (41). Flexibility is modelled to indicate what can be handled by the PA and what its limitations are, while the product variant creation indicates product differentiation points (19) and relates the PA to the currently known spectrum of achievable product variants.

Process flexibility enables the production of multiple product variants using the same equipment, enabling higher utilization of machines and the ability to react to changes in market demand between product variants (12). Process flexibility is communicated by modelling the part related parameter ranges available in the main stations and illustrating the known relevant part types that can be produced. Tools and parts are noted to provide information on what needs to be changed to achieve new product variants. Routing flexibility (41) can be modelled as alternative or optional interfaces using dotted lines.

Product related dimensions, geometries, and relevant material parameters that can be handled by the PA are modelled to allow identification of product variants that can be produced without further investment in the production system. As in the GPF, product differentiation points are modelled to identify the flow for each product variant and the number of product variants that must be handled at each step in the production system (30).

The production volume ranges within which the firm's production can remain profitable are modelled to communicate the volume flexibility (16).

### 4.3 Expansion

The future perspectives of the PA, including how scaling of the PA will be implemented are described. PA implementation decisions during development are necessary to increase the capabilities of the PA, whether dealing with how to increase capabilities during development or how to ramp up capabilities to prepare for product launch. These changes to the capabilities are the result of changes to the equipment or structure of the PA and can fall into two categories: Planned expansions for which implementation is to be initiated and potential expansions that are defined but will be implemented at a later stage. Potential expansions carry greater uncertainty. The planned and potential changes to the PA are modelled either as part of a single model, as in the GPF (30), or as a separate model, similarly to current and future state Value Stream Maps (VSM) (34). Each change in the structure or capabilities is colour coded to emphasize both what the changes comprise and their effect on the PA's capabilities.

# 5 Case study

The modelling framework was applied in a 100 Million DKK technology development project aimed at commercializing transducers based on Electro-Active Polymer (EAP) technology (42). Development was performed in parallel on the base material, production of the EAP-film and transducers, transducer design, high-voltage electronics design, and technology prototypes utilizing EAP-transducer prototypes. The project involved development of equipment and processes for the production of EAP-film and transducers. Specifications, capacity requirements, quality factors, and the supply chain design, were constantly changing and being identified during development. Decisions needed to be made on the design and implementation of the production system based on what it would enable in terms of production and development of EAP-products. The design needed to be communicated to diverse stakeholders to ensure that the production system would fulfil the needs of the firm and the project.

The case covers the pilot production of EAP film, a corrugated silicone film sandwiched between metal electrodes deposited onto the film, in various potential configurations (43). The PA comprised six main stations, twenty-eight individual processes, and two main flow paths. The number of explicitly stated film variants was twelve, but in addition to this number, thickness and width of the film could be varied by altering production parameters.

## 5.1 Modelling process

Initially, three PA models were created, each depicting a particular time in the development: (2011) the state before the project started; (2013) the plans being implemented at the time of the modelling activity; and (2015) the intended expansions at the end of the project (shown in Figure 3). The three models were presented on a single large poster that also contained capacity increase estimates and information related to project tasks. Decisions on the development and implementation were made with the support of the models. Revised models for the intended expansions at the end of the project were constructed to reflect the decisions.

The initial case models were created during a period of one month. This included two workshops with the participation of the production manager, process engineers, and the project manager on behalf of the case firm. Data collection for the modelling task included an analysis of the production facilities and review of existing but outdated production flow charts. The PA models were populated and updated between the workshops. Feedback was received on the drafts for refinement of the models and the modelling framework.

The models were implemented as standalone documents in Microsoft® Visio® and 3D illustrations were created in PTC® CREO® Parametric 1.0. Process icons were purpose made for the case. Large format paper printouts were used for all discussions and workshops.

## 5.2 Production Architecture models

The PA models—see Figure 3—described the structure, capabilities, and expansion of the EAP-film PA.

### 5.2.1 Structure

The models captured the elements of the PA and their relations; the main stations, critical processes, tools, storage and transport of material, and quality control (QC) stations. Each process included the primary process parameters that were related to achieving the desired film quality. The main stations were central production equipment or process groups and identified the chosen production technologies in each PA instance; in the case of the future state PA model these were the material mixing processes, film coating machine, de-lamination and lamination station, metal deposit machine, pre-conditioning station, and film coating tool cleaning machine.

The equipment level showed the dispositional links between main stations and product characteristics of the EAP film, i.e. breakdown voltage, film width, and lamination configuration. This identified where the production technologies and equipment affected the obtainable quality of the resulting products.

#### 5.2.2 Capabilities

Product flexibility of the main stations was indicated as the available range in major film parameters; film thickness, width, length, and corrugation pattern. Product variant differentiation points were illustrated by basic film configurations. Volume flexibility was indicated as the maximum capabilities as the production task was focused on prototype production and demonstration of production volume scalability. Cycle times for a film roll of a certain length, width, and thickness were noted for each main station in the PA model of the production system at the outset of the project, and as relative improvements in the current and future state PA models.

#### 5.2.3 Expansion

Decisions to be made regarding investments in new equipment critical to the production process were identified and communicated through the PA models. Intended and implemented scaling of capabilities were noted as improvements from the PA at the start of the project. The changes included new equipment, flow path changes, product variant production capabilities, dimensional capabilities, and production capacity capabilities. In the models for 2013 and 2015, updated main stations from the 2011 model were indicated by a green border. The production capacity expansions were noted as relative output increases. The resulting PA models were used to communicate the intended expansions to the PA and their expected benefits to other stakeholders, for whom an understanding of the PA was valuable either for their own work or for making implementation decisions regarding the PA. The models shown in Figure 3 were used during discussions on the development of the PA and what to implement. Discussions on the benefits of implementing equipment—indicated in the models through capability modelling elements—and development hurdles lead to decisions to change the expansion plans. New model instances were constructed to reflect the changes to the implementation plans. The main changes due to not implementing a combined de-lamination and lamination process are shown in Figure 4. The left side of

Figure 4 shows the model for 2015 from the initial modelling activity. The right side of Figure 4 shows the updated model with the implementation at the end of the project.

### 5.3 Reception of the models in the case project

The industry implementation facilitated discussions within the production development team on the production and the parameters involved. These were described as being clearer to the team after the modelling process than before. The sheer number of elements of the PA and parameters involved made the overview provided by the PA models valued by participants. Some of the statements made by participants on the value of the models are quoted below:

- "Hearing how the production team was able to use the models for communication—internally and externally—showed me that it was a good solution. The production team could use it and explain it and use it to explain to others what the production was all about."
- "The information on the production system that was hidden inside our minds has been visualised in the models"
- "It's good to use with people that do not have the in-depth understanding of what our production system is about"
- "The models give us an overview of the solutions and where potential changes may affect the following processes—do they have a detrimental effect on the other processes?"
- "We needed to communicate what is the activity, what is the process, and what is critical—this is captured in the production architecture models"

## 6 Discussion

The PA modelling framework is evaluated against the required contents listed in section1.2.

### 6.1 Structural elements of a PA

The structure of the PA—it's sub-systems, equipment, production technologies, and their relations (1,7,9)—is described at a level of detail suitable for use during technology development. The physical elements of the PA and their functional relations can be identified, while their physical structure and the PA layout are omitted. The main focus during technology development is to prove the ability to produce products and investigate obtainable quality, which was supported by the PA modelling framework. The scale required for commercial production volumes—where layout design is important—was not being reached at that point. Identifying dispositional links to the product architecture (10), quality parameters (22), and incorporation of quality control points (20) is supported by the PA modelling framework.

### 6.2 Functional elements of a PA

The proposed models include capability descriptions fulfilling the requirements. The PA models indicated the obtainable product quality, described the capabilities within product flexibility, and plans for scaling up production volume. Batch sizes and processing times were included as scaling volume up to industrial production volumes is an important factor in technology development (21,22), but cost, economical production volume, setup times, and buffers for partially produced goods were omitted as these were considered to be of little relevance during the level of technology development reached within the project.

### 6.3 Expansions to the PA

The expansion modelling in the case study focused on the expansions to be implemented within the project. Decisions on expansions in the case project were modelled in two ways in the models: (i) The explicit modelling of decisions yet to be made by the production development team and (ii) the implicit modelling of decisions made by the production development team, modelled as planned expansions. The models supported decisions to change expansion plans as the resulting capability expansions were deemed to not be necessary within the scope of the technology development project. System models support decision making through modelling of those consequences of decisions that are most relevant to the aims of the development task (44). The results of these decisions were then reflected in updated models that show what was actually implemented and communicated the results to relevant stakeholders.

### 6.4 Use of the PA models

The industry implementation showed that the PA models could be constructed within a short time period using a well known software package using limited resources and were suitably scoped to the needs in the case—important aspects of a model's practicality (45).

The feedback from participants clearly stated that the models supported identification of critical parameters and decisions to be made regarding the PA. The modelling process itself was also noted as a valuable catalyst for discussions and identification of parameters.

The common, simplified perspective (46) provided by the PA models facilitated exploration of the PA by heterogeneous stakeholder groups. Observations of the PA models as focal points for discussions support previous results on the value of architecture models and graphical descriptions as means to facilitate communication between heterogeneous stakeholders (3,47).

### 6.5 Research limitations

The research is limited to one case project. However, while any case can be considered unique, there are elements in the industrial project that can be of relevance for other firms and other industries. The main focus of the framework is modelling the production architecture during technology development to support investment decisions—with uncertainties regarding product and production architectures. Technology development occurs in conjunction with product and production development in other industries, where these circumstances also arise (48). The development of production processes to increase obtainable product quality and production capacity is also described in literature involving other firms (21). Furthermore, the modelling framework is founded on theoretical literature on systems and production modelling, production system design, and production flexibility. Therefore, it is likely that there are other firms in industry that could benefit from applying this modelling framework.

## 7 Conclusion

During technology development, before the products have been fully defined, it can be necessary to invest in production equipment to obtain production capabilities to e.g. determine obtainable product quality on industrial production equipment, produce prototypes, and develop production processes. To obtain fitting production capabilities, it must be identified what constitutes fitting capabilities, what elements of a production system must be taken into account, and a decision must be made on which production capabilities shall be acquired and how. The structure of the production system must be identified, the capabilities of a production system with that structure must be determined, and the expansion of the capabilities through production system development should be decided. A modelling framework, aimed at supporting the development of a Production Architecture (PA) concurrently with development of a product architecture from an early phase, the PA modelling framework, is proposed. The modelling framework builds upon and combines elements from existing literature to capture and present the structure, capabilities and expansions of a PA during development. The contribution of this work lies in modelling the combination of structure, capabilities, and expansions during technology development.

A case study presents the implementation of the modelling approach in industry during technology development with parallel product architecture and PA development. Case study results indicate that (i) the modelling process facilitates identification of critical PA parameters; (ii) the framework captures and presents implicit and explicit decisions made, or to be made, by the production development team; (iii) the resulting models facilitated dialogue between heterogeneous stakeholder groups and by confronting recipients with a concrete perspective on the PA and its capabilities; (iv) the framework is fitting to be implemented in a dynamic, uncertain, environment at an early phase of development.

The validity of the framework lies in its theoretical foundation and its implementation in a case study in industry. The implementation in an industrial case within the intended environment where decisions were made within a heterogeneous group of stakeholders was considered valuable. As the framework is developed on the basis of a broad theoretical foundation and literature has examples of cases where product and production development is performed concurrently from an early phase, it can likely be transferred onto other, similar, environments.

Further research opportunities include further testing iterations to refine the framework; implementing the modelling approach in more projects; implementing the framework in a project where it could be followed from technology development until handover to mature new product development processes; and identifying how the framework can interface with more mature development processes..

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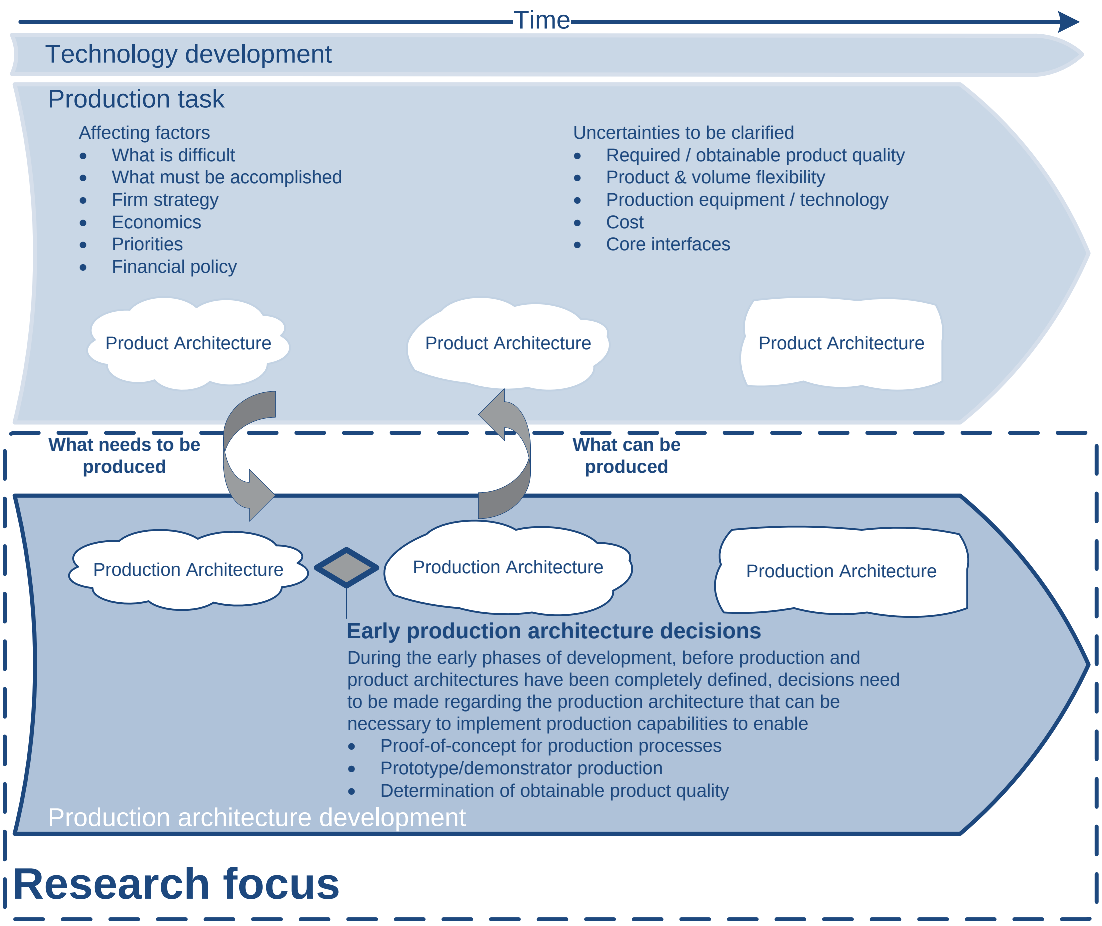


Figure 1: The definition of the production task and the production architecture is gradually made more complete during development.

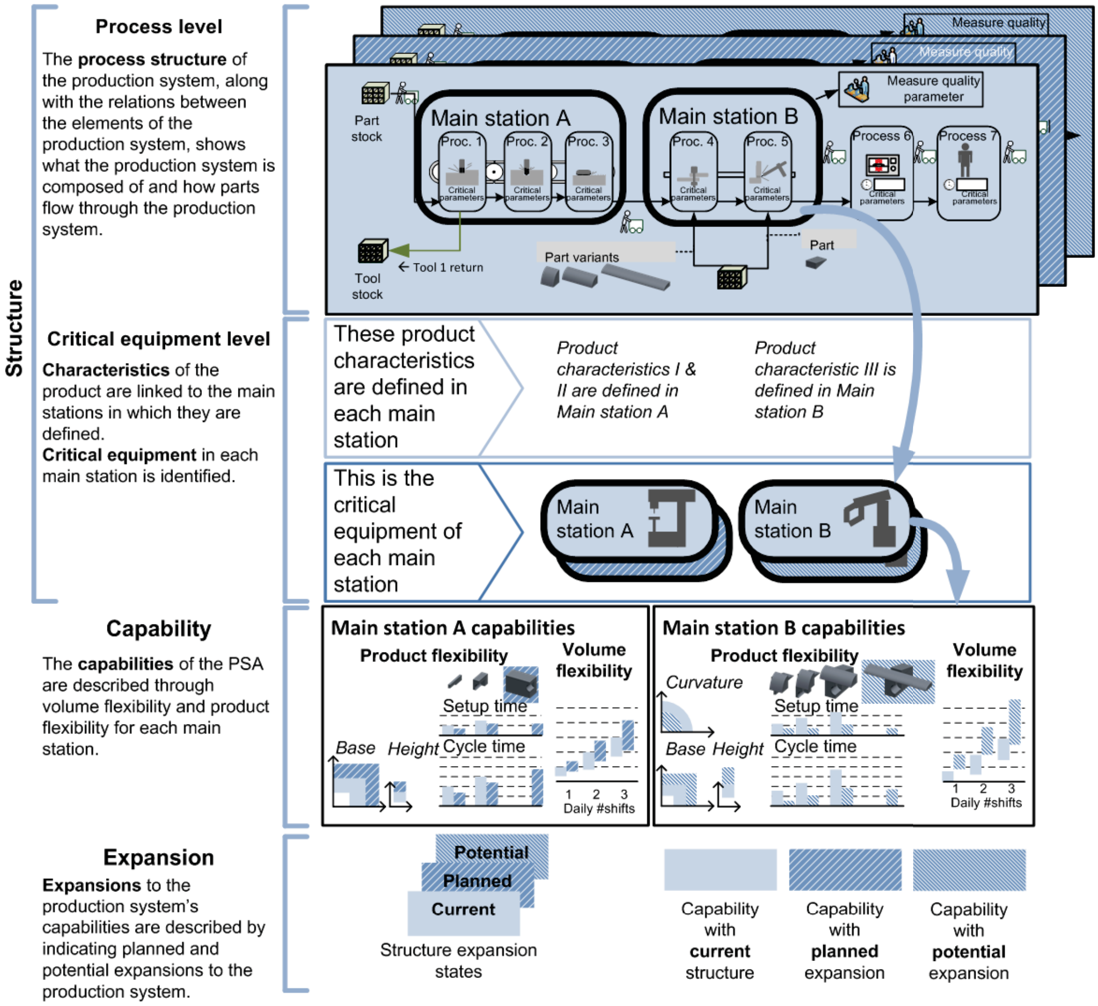


Figure 2: A PA model includes structure, capability, and expansion dimensions to support early PA decisions.

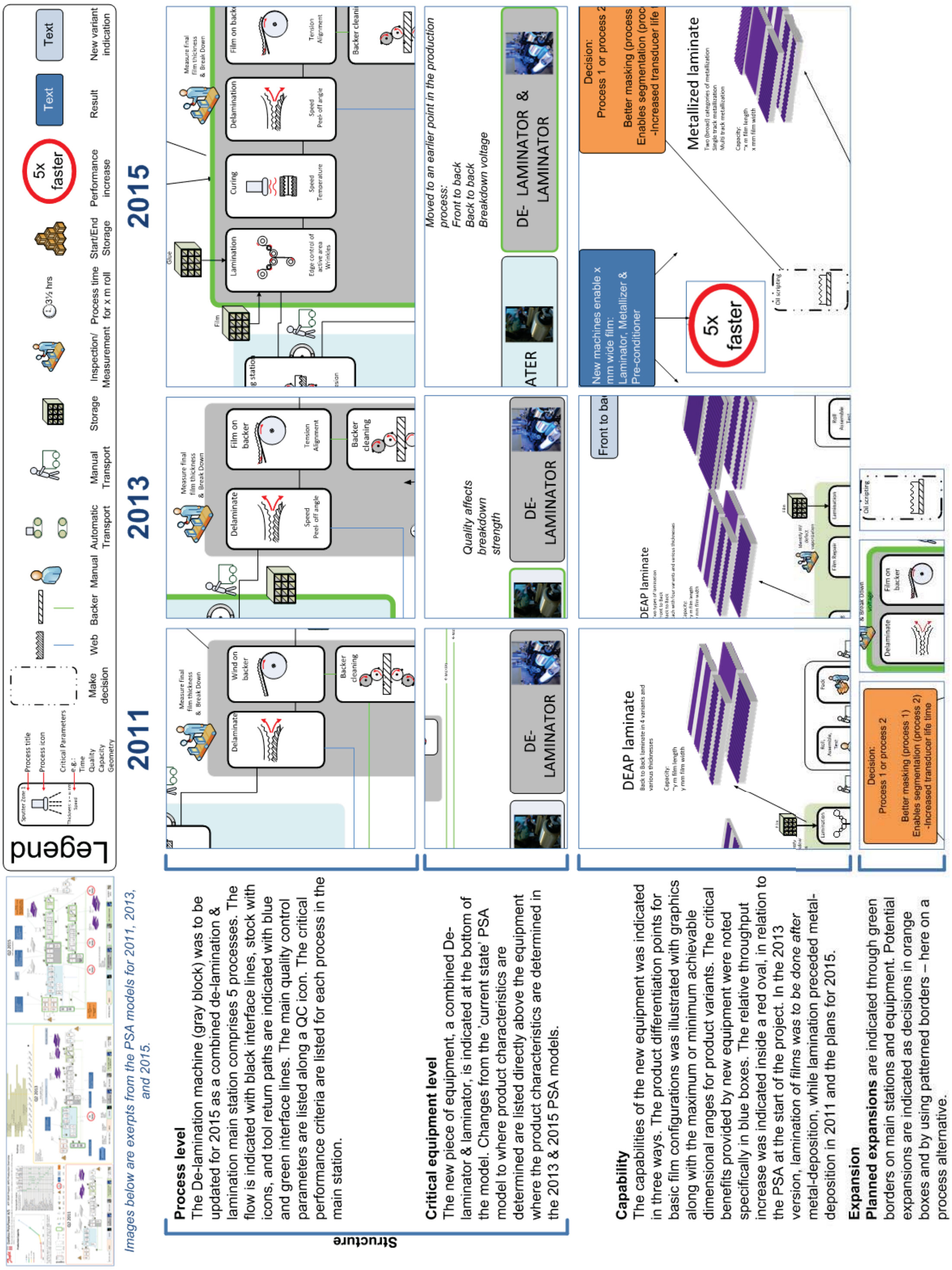


Figure 3: The PA models supported identification of the structure, capability and planned expansions of the PA.

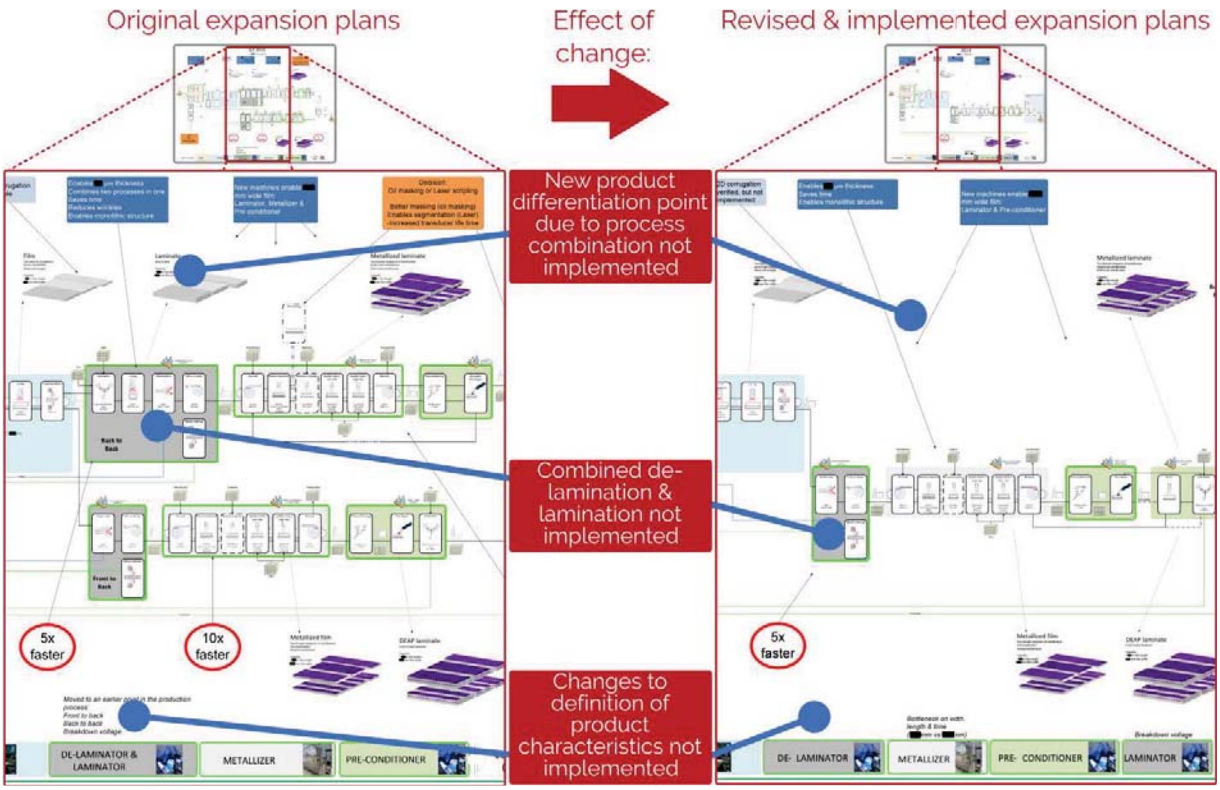


Figure 4: The effects of not implementing a combined de-lamination & lamination process can be seen when comparing original and revised (implemented) expansion plans.

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