APPLICATIONS OF THE THEORY OF TECHNICAL SYSTEMS - EXPERIENCES FROM THE "COPENHAGEN SCHOOL"

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1. Introduction

We dare to claim that no group exists, where the influence of Vladimir Hubka has been as strong as the Engineering Design and Product Development group at DTU; the "Copenhagen School" as our friends often refer to us as.

This paper uses the development and applications of Hubka's Theory of Technical Systems (TTS) at DTU as an example of the power of the theory, the necessity of detailing and fitting the theory, and the role of a theory as a basis for research.At the same time the paper is a balance of the influence of Vladimir Hubka and a short historical sketch of the incidental nature of our group's introduction to Vladimir Hubka, which led to lifelong cooperation and academic development.

Results have been obtained in the areas of DFX, workbench-based design, mechatronics, product development, and multi-product development. Across all these areas we have created a version of TTS with substantial applicability and coherence. This article does not show details on all of the research projects (which may be found in the literature), but it shows directions taken from Hubka's TTS and the contributions made in academia and through industrially applied research.

2. The beginning

Professor Vagn Aage Jeppesen established his chair on engineering design in 1952, founded upon a philosophy of design based upon creative thinking [Alger and Hayes 1964], product development [Azimow 1962], systematic (sparse signals from Germany), and deep understanding of industrial practice. He was very devoted to teaching systematic approaches and to bringing them to industry, and was the first engineering design professor in Denmark.

Vladimir Hubka visited Denmark in the summer 1968 together with his family. He had a meeting with Vagn Aage Jeppesen, where Hubka told about his book manuscript on TTS and his ideas and where he listened to Jeppesen's endeavours, already crystallised into new courses on engineering design and projects. Few days later Hubka returned to DTU, now a fugitive because Soviet troops had invaded Prague and Hubka knew that he was seen as "politically unreliable". Jeppesen hired him as design engineer in the Institute of Product Development, a foundation independent of the university, aiming at industrial consultancy and practical product development.

Supported by study groups and practical product development projects (among these creation of an egg sausage machine for industrial production of hard boiled eggs) we built up a joint understanding, which did not disappear when Hubka left Denmark for a position at ETH in Zürich, but grew in many directions and importance in the following years.

3. Tjalve's book 1976

Hubka's theory of TTS is based upon system's theory [Ashby 1956], [Klir and Valach 1967] built on a strong devotion to classification and systematics. Eskild Tjalve, a staff member in our group from 1970-84, was distinctly graphically and creatively gifted. Based upon his teaching and design experiences and combined with TTS and Hubka's theory on the engineering design processes, Tjalve wrote the book "Systematic formgiving of industrial products" [Tjalve 1976] in 1976. This marriage of strict methodology and the use of graphical methods (see fig 1) were so unique that the audience was puzzled. The English publisher insisted on calling the book "A Short Course on Industrial Engineering" and a reviewer of the German edition [Tjalve 1980] only focused upon the relation between engineering and industrial design.

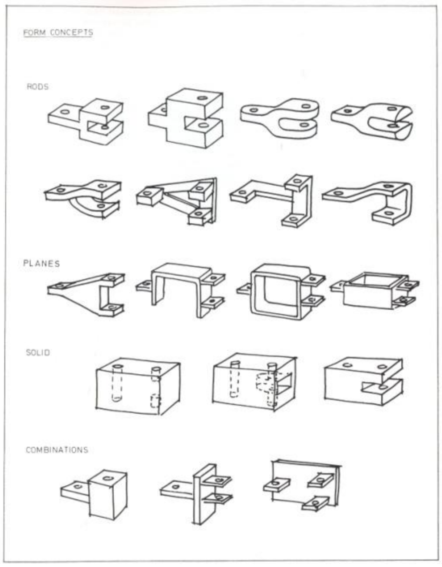

Fig. 1. An often-quoted illustration from Tjalve's book showing form concepts based upon form variation [Tjalve 1976]

Tjalve's book, whose German edition was elaborated by Hubka (and also translated into Polish, Russian and Portuguese), distinguishes itself as a practice-oriented and highly inspiring textbook, and appears as a pedagogical elaboration on Hubka's theories. Its simple, yet clearly focused design synthesis procedure, its balance of systematic and creative methods, the philosophy of product life concerns and product usability, and the power of his graphically supported methods, make this book a classical work on designing.

4. Andreasen on methods for synthesis 1980

Through the 70'ies our group empowered its insight through a long line of product developments for industry, through performing company internal courses on design methodology for Danish industry, and from a growing palette of courses on engineering design. As a 'tour de force' on methodology, aiming at a comprehensive understanding of synthesis methods, Mogens Myrup Andreasen wrote his thesis on "Machine Design Methods Based on a Systemic Approach, - a contribution to a design theory", defended at the University of Lund, Sweden, in 1980 [Andreasen 1980]. It was written in Danish in order to create a Danish terminology, but at the same time hiding for foreigners the fact, that "the thesis is an exaggeration of definitions", as Sidney Gregory wrote in a review.

Hubka's theories and methodology were the core of the thesis' scientific foundation, and Andreasen allowed himself to baptise two of Hubka's contributions as Hubka's first and second laws, see fig.2. The main contribution from Andreasen's thesis was formulated as a "Theory of Domains", i.e. seeing designing as reasoning and creating synthesis in a domain of activities performed with the product (the product's purpose and satisfaction of human needs), a domain of organs explaining the functionalities and the properties of the product, and a domain of parts, explaining the materialisation and building up of the product, fig.3.

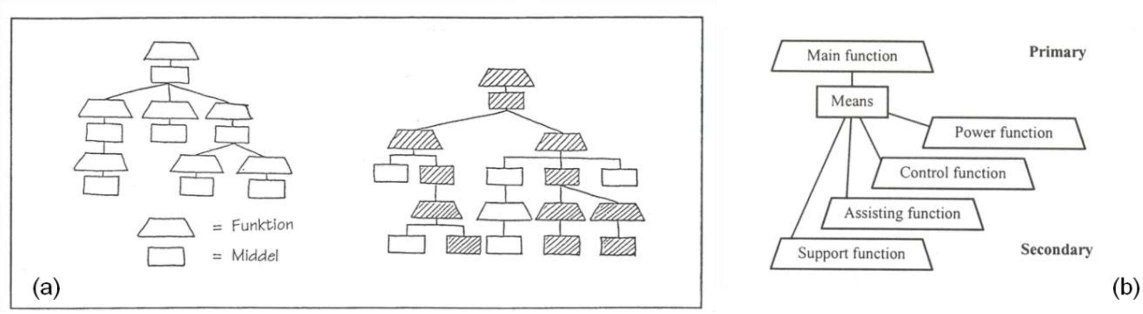

Fig. 2. Hubka's fist law (a) and second law (b) illustrated by [Svendsen 1994] and [Jensen 1999]

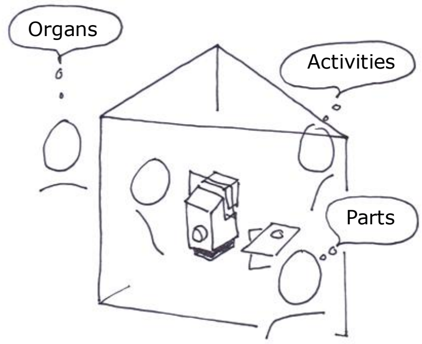

Fig 3. Popular illustration of the Domain Theory's three views upon a product and its use activity, [Andreasen 2007]

In each of these domains systems models can be established each with different views upon elements and relations. The most important aspect of the Domain Theory is the arbitrary, but essential distinction between characteristics [Merkmale, Hubka: Design properties], which define the systems, and properties [Verhalten, Hubka: External and internal properties], which describe the behaviour and functions.

5. Design for Assembly, first DFX step in 1982

In the book "Theorie der Maschinensysteme" from 1974 [Hubka 1974] Hubka identifies a line of principles concerning the qualities of technical systems, formulated as "Design for…", i.e. principles for fitting a design to manufacture, assembly, distribution, sales, use etc. In the research world these areas were developed throughout the late 80'ies and reached a peak of interest in early 90'ies [Andreasen 2001]. Powerful industrial tools were launched around 1980.

At DTU the industrial interests in assembly automation rose in the late 70'ies and our group performed several industrial tasks on developing and building machinery and teaching design for assembly in industry. We structured our experiences in the books "Design for Assembly" from 1982 [Andreasen et al. 1982] and "Flexible Assembly Systems" from 1986 [Andreasen and Ahm 1986]. Three basic views from TTS were established:

- The *assembly process* is described as a system of activities, showing how the parts (operands) were brought into the assembly structure by assembly equipment or humans (operators).
- The *assembly equipment* is seen as a system, described by its functionalities and by the characteristics that are important for the assembly.
- The *product* is seen as a system of parts and identified by the characteristics of these parts and their relations of importance for assembly.

This structure allowed us to crystallise and illustrate a long line of principles for DFA, linking statements on the product's characteristics to statements on the equipment's characteristics and pointing out what effects following the principle might have. We used costs and assembly time as metrics and we saw the principles as 'conditionally valid', i.e. it is up to the designer to control if there is validity and effects to be reached in a certain situation.

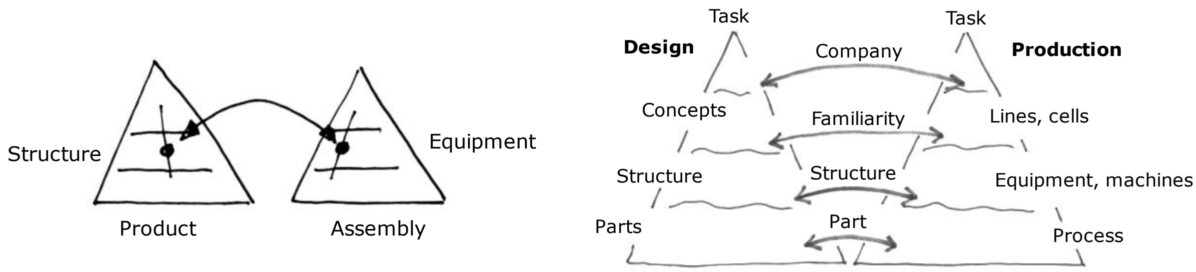

Fig. 4. A typical DFA rule is here used to illustrate the general nature of a DFX principle. High level principles are most powerful, [Andreasen 2007]

The challenge of creating product variants, satisfying a spectrum of users' needs, but without raising the production complexity, and the challenge to create assembly systems showing the necessary flexibility, was our focus for the second book. Here we laid the basis for modelling of products and machinery in such a way that we got insight into functional- and building structures [Baustruktur] relations, of importance to Design for Variety and Design for Flexibility.

6. Mechatronics: Buur 1990

Danish industry is dominated by mechatronic products and the interest for establishing new educational initiatives led to the establishment of a Danish Association of Mechatronics. Our group was active in industrial study groups, in establishing new courses, and in the formulation of mission, vision and contents of this new area.

In 1990 Jacob Buur defended his thesis on "The Theoretical Approach to Mechatronics Design" [Buur 1990]. His studies of mechatronic industry, especially in Japan, and observations of industrialists designing mechatronic systems led to his justifications on the nature of such systems: They comply with TTS and the domain theory. They may be treated by functional reasoning cross-disciplinarily. They follow the pattern of the function/means-tree (Hubka's 1. law). Buur's most remarkable results are his clarification of the concept of function and his identification and understanding of software as an element in a mechatronic system. He also introduced the state transition phenomena, fig. 5, as a general product aspect, surprisingly disregarded in mechanical engineering.

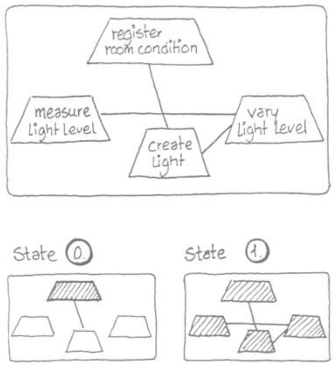

Fig. 5. A characteristic simple example from Buur's thesis: The structure of an intelligent lighting system, showing state transition [Buur 1990]

7. Our dream about a Designer's Workbench in the 90'ies

Our cooperation with Pedro Ferreirinha, a pupil of Hubka, co-operator in our informal society "Workshop Design Konstruktion (WDK)", and the owner of an industrial consultancy in Switzerland, guided us into the goal of creating a Designer's Workbench. Ferreirinha's ideas were superior to ours; we had the staff and financing for making research.

The basic idea behind the workbench was to utilise the Domain Theory to establish a three domain model, a Chromosome as Ferreirinha called it [Ferreirinha et al. 1990], to compose the structural definitions of the product related technical activities, the organs and the parts. It was recognised [Andreasen 1992], that such a workbench should contain or be based upon:

- *Design language*, i.e. a vocabulary for thinking, reasoning, conceptualising and specifying solutions in all three domains, based upon semantics and syntax, and equally fitted for human reasoning and computer operations.
- *Design models*, i.e. models for structures of activities, organs and parts, carrying the specifications of these structures and allowing more or less formalised specification of relations inside and between the domains and of property statements [soll/ist] of the entities.
- *Design operations*, i.e. methodologies for synthesising, composing, evaluating, modelling, simulating etc. for a gradual synthesis in all domains.

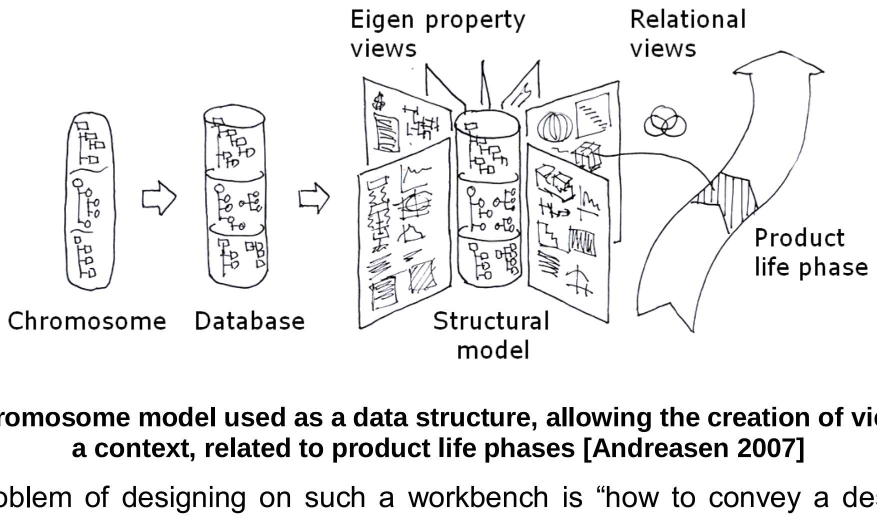

Fig. 6. The Cromosome model used as a data structure, allowing the creation of view models in a context, related to product life phases [Andreasen 2007]

The core problem of designing on such a workbench is "how to convey a design into the computer". In CAD systems one defines the artefact stepwise from elementary, geometrical entities, or one imports lumps of structurally defined solutions. Our early imaginations were to use so-called *masters* for certain classes of design, which would consist of pre-filled models of frequent solutions.

7.1. A database for aluminium design, ALULIB 1992

Our early ideas found an application, because we were asked to create a database of applications of aluminium for designing products. Chromosome models were established for the organs and parts domains for selected products with interesting application of aluminium. Due to the fact that these products' goal specification; organ characteristics; organ functions and properties; parts characteristics; and parts properties were interrelated in the database for each product, but at the same time accessible across products, a designer could search on functions, organs properties and part geometry, and trace their role in the product. Organs and parts were documented pictorially, with easy search mechanisms [Mortensen 1992].

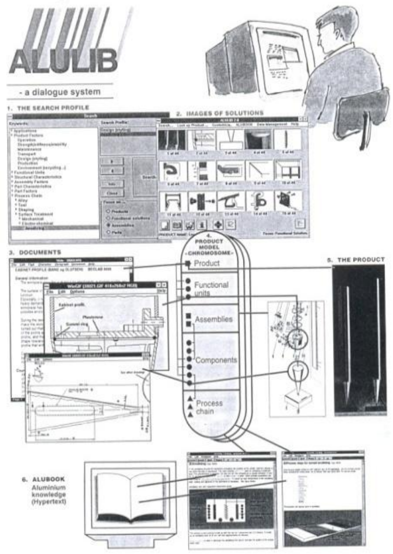

Fig. 7. A brochure page for ALULIB, showing screen-dumps and relations to ALUBOOK, an information system for aluminium technology [Mortensen 1992]

The software was distributed from ScanAluminium for users in Scandinavia, and the response was positive concerning its ability to supply engineers with new and interesting solutions and to guide their attention to the connected database with information on aluminium technology. We saw the system as a first proof that our workspace ideas were feasible.

7.2. Decomposing and composing on a workbench, Svendsen and Hansen 1994

Our results from ALULIB, our experiments with a computer based system for design of bearing systems, CADOBS [Andreasen et al. 1988], and the use of the design language TEKLA conceptualised by Ferreirinha [Andreasen et al. 1990], was the background for the formulation of a general specification and structure for a workbench, based on several publications on structuring of product data, product modelling, product developments functions in a workbench, and elaborations on a design language.

Svendsen [Svendsen 1994] took up the task to investigate on the handling of composed products in a workbench. Imagining a running design activity the task should be decomposed, controlled by decomposed goal formulations and identified sub-solutions, and these solutions has to be composed into a totality, controlled by balancing of properties. As a precondition Svendsen saw the use of pre-identified elements (functions, features, organs, components, and master plans). Decomposing may be function-oriented or pragmatic, but the designer's experience or ability to predict are of immense importance.

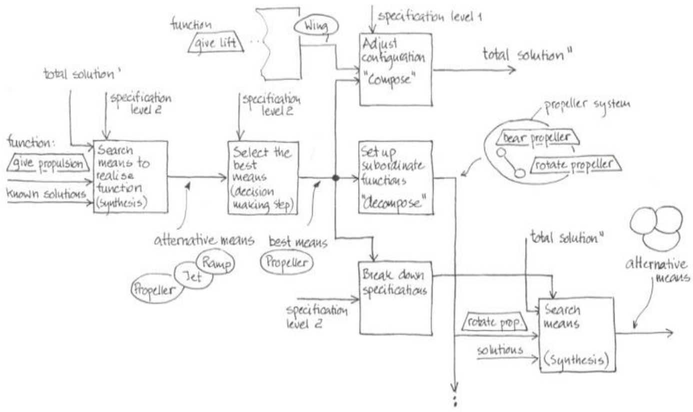

Fig. 8. Model showing decomposing/composing activities influencing specification breakdown [Svendsen and Hansen 1993]

The design and navigation in the solution space (performed in simplified design experiments) was supported by function/means tree structures, and was followed by goal decomposition operations and goal balancing. The research showed us fundamental limitations in our current research and the superiority of the human brain's ability to synthesise [Svendsen and Hansen 1993].

7.3. The organ domain explored, Jensen 1999

Thomas Jensen's research on functional modelling [Jensen 1999] created basic insight into the nature of organ and part structures and especially their relations. He saw organs as structures of *wirk elements*, showed how *wirk elements* are the carriers of design intent, and how behaviour of a structure should be seen as a state transition (!). His identification of structural organ attributes or organ characteristics led to his proposal that functional design on a workbench should be based upon reasoning about organ units, i.e. knowledge elements clustering function and behavioural insight into functional building blocks, fig. 8.

Thomas Jensen's combined theoretical and experimental approach, using paper-based prototyping of software and experiments with design engineers, gave us insight into functional reasoning in dialogue with a computer "asking for reasons" and showed us the difficulties and limitations of our workbench concept.

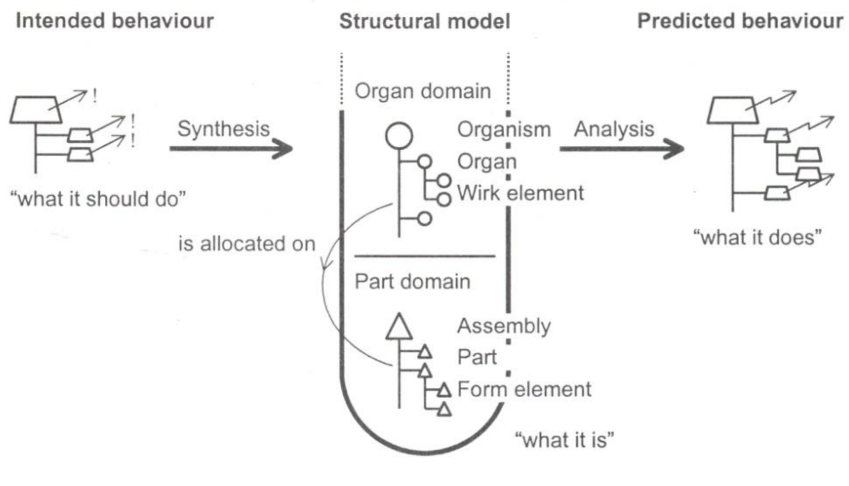

Fig. 9. Designing based upon reasoning on *wirk elements* and their physical realisation in the part domain [Jensen 1999]

7.4. Modelling in a workbench, Mortensen 2000.

In his thesis [Mortensen 2000] aimed at establishing the design language for modelling the three structural domain models and their relations in such a way that they function in a designer's workbench.

His elaborations on part structure language, part design theory, modelling of product and related activities in the product life cycle, and the establishment of so-called view models able to show functionality and properties of the product, lead to the creation of a Generic Design Model System. This system is able to cope with characteristics and properties in all the domains. Mortensen saw properties in "design preparation", i.e. to create such generic models and knowledge which mirror a specific company's assets. And he saw the system's power to carry a company's product assortment.

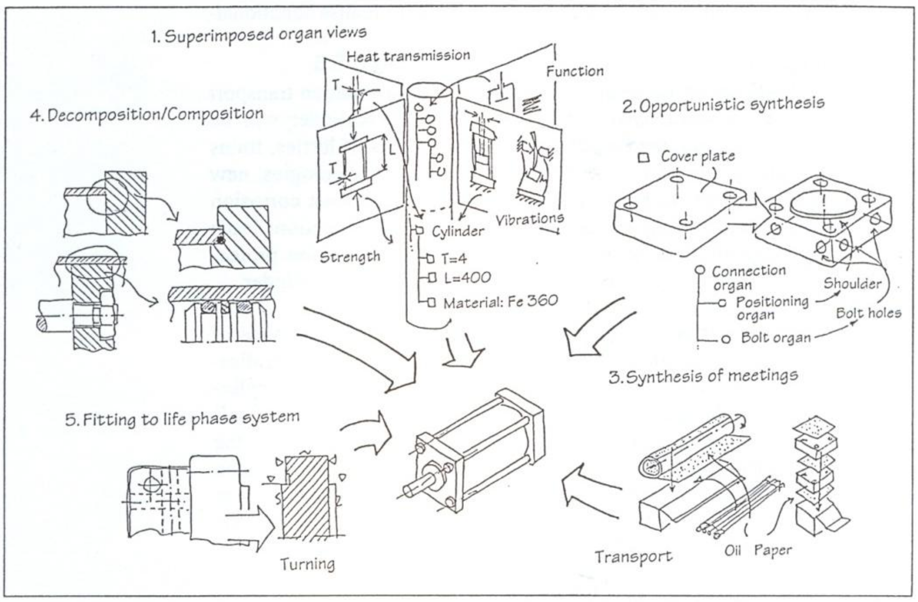

Fig. 10 Illustration of exercise on modelling synthesis related to the Generic Design Model System, showing views [Mortensen 2000]

When Mortensen finished his thesis, the topic of modularisation had emerged in industry and academia, and the group was already heavily involved in research on modular structures. We saw a high potential in applying our domain models for modularisation and therefore gave up the workbench line of research and aimed at multi-product development, as described below.

8. Integration, concurrency and product life thinking in the 80'ies

In the 70'ies manufacturing companies organised themselves in more specialised functional units for obtaining higher knowledge and utilisation of resources. The design activity suffered from this, becoming decomposed, and new means for organising design such as matrix organisation, teamwork and integrated execution were established. It also became evident that the creation of competitive products required more than engineering and we had to begin to see product development as the framework, in which engineering design was performed [Andreasen and Hein 1987].

Hubka shows in his "Theorie der Konstruktionsprozesse" [Hubka 1976] and later in "Principles of Engineering Design" [Hubka 1982] how the basic pattern of the engineering design process is determined by the gradual and causal synthesis of the artefact. This important role of an artefact theory has been overseen for years, but underlines the importance of Hubka's articulation of TTS.

The principle of seeing the artefact's design as the backbone of designing was also used in Andreasen & Hein's "Integrated Product Development" [Andreasen 1987] for the modelling of the product development activity and letting market and production activities be aligned to this structure. The book was not seen as a research document, but as an essay and a textbook for self-study for industry. The strict distinction between engineering design and product development, which we unfortunately do not yet see respected today, was appreciated by the market-, sales-, supply-, production-, and distribution managers in the companies, who saw their "task, roles and rights" articulated and confirmed in the book.

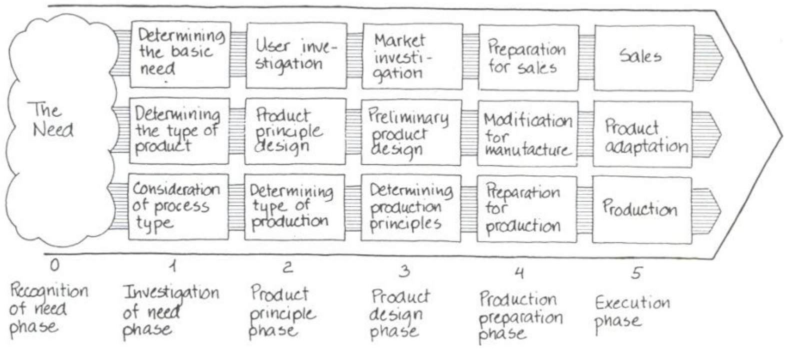

Fig. 11. Generic model of an Integrated Product Development project, showing the concurrency and simultaneity of activities related to market, design and production [Andreasen 1987]

Seen from a TTS point of view the book underlined the importance of understanding characteristics and properties of markets, production, products and the established business, articulating goal documents for all domains, and the integrating mechanisms, first of all the DFX methodologies (but also organisational and information flow integrating mechanisms).

The campaign in Danish industry created better understanding of the role, management, staging and results of product development, and the gradual articulation of the design result as the "clockwork" of the product development activity.

8.1. Theory of dispositions, Olesen 1992

Hubka pointed out that important criteria for a product's goodness come from the product's life phases, and he saw the designer as responsible for the product's "fitness for life" just as Tjalve. Olesen dug deeper, asking for the relations and mechanisms in the product life's influences on the product and vice versa [Olesen 1992].

Olesen saw each life phase as a transformation system with certain characteristics, influencing and influenced by the product in what might be seen as optimal performance in the actual life phase. Simplified he spoke about the product's 'meetings' and used Tjalve's pyramid for design characteristics, see fig 12, for identifying the governing pairs of characteristics. Each life phase is seen from the viewpoint of stakeholder(s), whose criteria for optimal performance has to be found between: cost, quality, time, efficiency, flexibility, risk, and environmental effects, the so-called Universal Virtues, or properties of an activity, see fig 12.

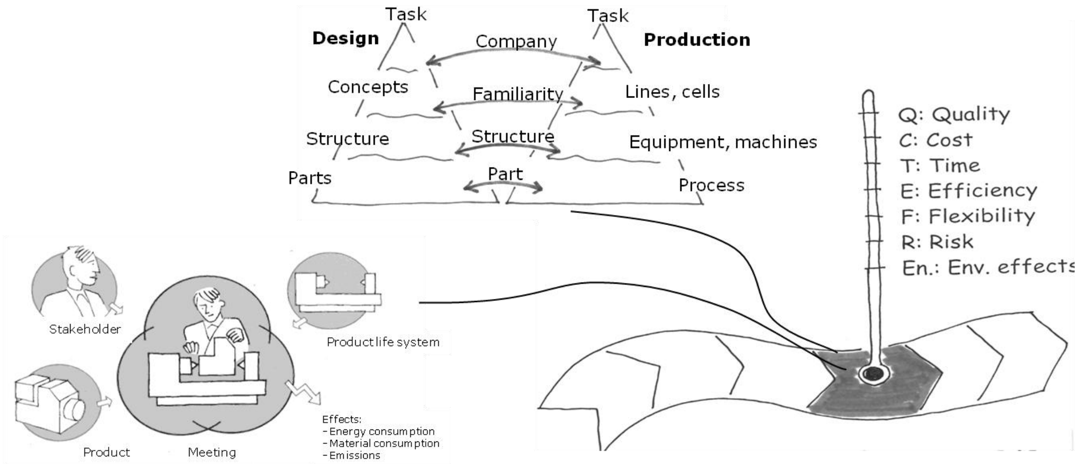

Fig. 12. In each product life phase the product joins a meeting, where the identification of characteristics and their alignment may lead to better performance, measured by the Universal Virtues [Olesen 1992]

The influence Olesen was seeking for he called a disposition, i.e. that part of a decision made in one activity which affects the type, content, efficiency, and progress of activities within other functional areas, see fig 13. By this establishment of a language for activities' characteristics and properties, Olesen formulated a matrix of "all DFX areas", the so-called DFX Matrix, fig 14, and his theory of dispositions may be seen as a general theory of all DFX areas, covering a mesh of product life and universal virtue concerns.

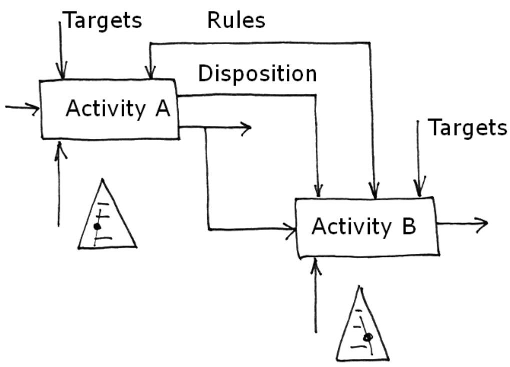

Fig 13. A general model of a disposition between two functional areas A and B, [Olesen 1992]

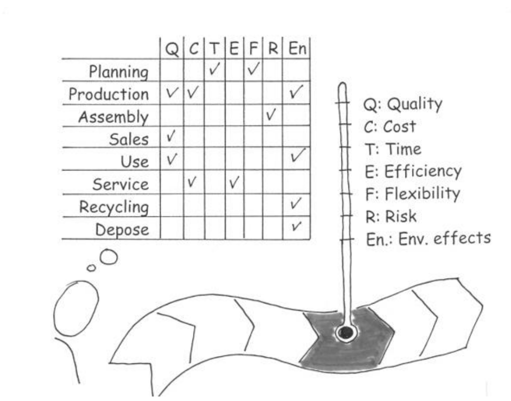

Fig 14. Matrix of product life activities and Universal Virtues, showing the total field of DFX areas. The ticked areas may be a specific company's areas of concern [Olesen 1992]

Olesen articulated his findings in a new model of establishing concurrency, the so-called *Score Model*, and articulated how relations between existing, adjusted or new developed product life systems should be used in an alignment of products, functional areas in the company and product support outside the company. Later Olesen joined our group as post doc researcher for the development of Design for Environment methodology, based upon his contributions, as described below.

9. DFX developments in the 90'ies

Olesen's thesis gave us, as mentioned, the Theory of Dispositions, which we see as a general theory of DFX, and allowed us to distinguish between X's which are product life phases (e.g. assembly), and X's which are universal virtues (e.g. cost, quality), see fig 14.

9.1. Design for Quality, Mørup 1993

Hubka saw quality as the perceived and resulting evaluation of a product's properties. The maximal obtainable quality is seen as ideal, desired value. Mikkel Mørup's point of departure in his research [Mørup 1993] on quality was a recognition of the partly subjective nature of quality and symbolic, emotional and social aspects of a product's value - and the recognition that DFQ was in its infancy. In spite of TQM efforts the results of quality focus in companies were sparse.

Mørup's quality definition states: "Quality is the customer's experience (or perception) of how well the totality of quality properties of a product satisfies his stated or implied needs". However, the customer is not one person, but may be split up into two groups of stakeholders, related to two kinds of quality:

- Q-quality ("big Q"). Q is the customers' qualitative perception of the products' goodness
- q-quality ("little q"). q is the internal stakeholders' qualitative perception of the products goodness in relation to their product related tasks.

Mørup points out the many internal and external stakeholders throughout the product's establishment and life that should be respected in the design process.

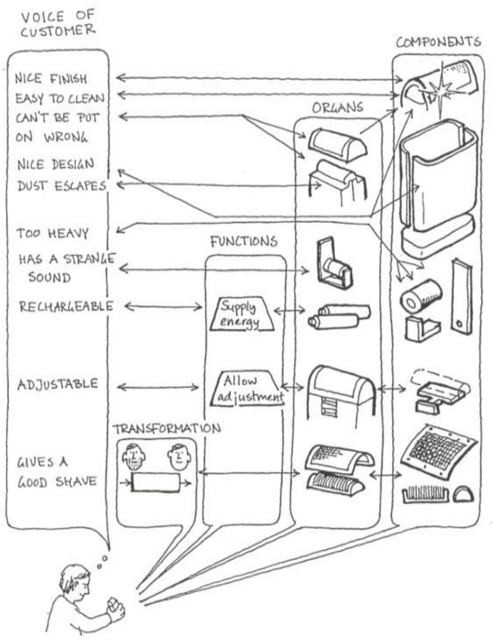

Fig 15. The Q-qualities of an electric shaver carried by transformation, functions, organs and parts [Mørup 1993]

Based upon the Domain Theory Mørup treated the relations between transformation-, function-, organ-, and parts characteristics and perceived quality Q, see fig 15. Danish industry received these new concepts with enthusiasm, because they were leading to new ways of specifying and discussing quality. Mørup advised 8 elements of DFQ-efforts in a company, related to strategy, organisation, methods and especially a DFQ mindset. We believe that the notation of customer defined quality and the non-analytical relation between perceived value and designed properties was the most important for our industry.

Related to Mørup's work Peder Andersson wrote his thesis in 1996 [Andersson 1996] on robustness, based upon a product modelling approach, related to life phases and focusing on conceptual design. Furthermore, Benny Matthiassen wrote his thesis in 1997 on design for reliability and robustness [Matthiassen 1997], diving deeper into mechanical products' nature, and crystallising 22 general design principles.

9.2. Design for Use and Usability

The concept of Design for Use is not frequently found in literature; because of influences from other research areas, Interaction Design or Design for Usability are more popular.

Tom Hede Markussen defended his thesis [Markussen 1995] on interaction Design in 1995. The basic idea was to identify the operational characteristics or the design degrees of freedom determining the goodness of a product's use. He advised that an engineering-wise approach (grounded on causality based structures of the design object) and an experience based approach (grounded in user's and designer's experience of, and reaction to, the design) should be balanced. Marcussen continued the graphical line after Tjalve, adding a rich spectrum of prototype-related scenario techniques for "designing the use", and covering different aspects of use, see fig 16.

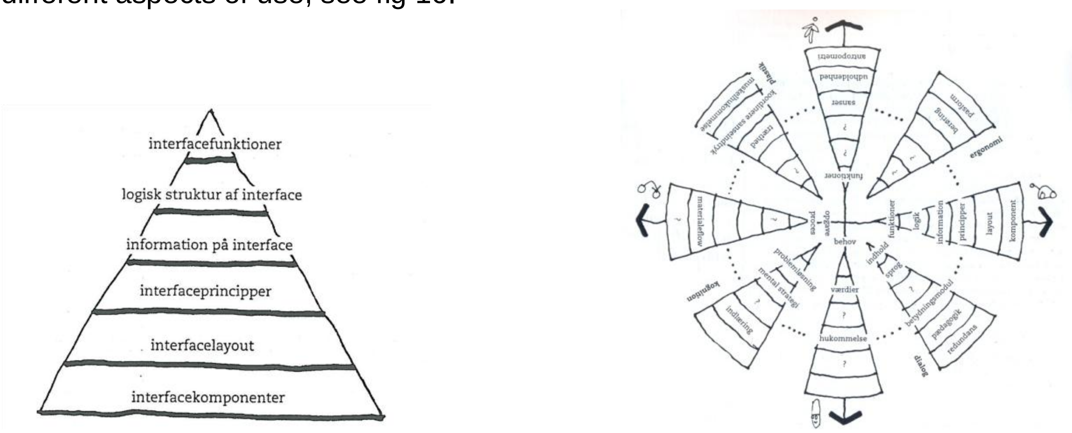

Fig. 16. The design degrees of freedom of a product's interface, and the mapping of approaches to identifying the use activities [Markussen 1995]

Pi Nielsen [Nielsen 1999] defended her thesis "Design for Usability" in 1999, focusing upon the handling (mounting, ready making, use activities) of products. She confronted TTS with HCI (human-computer interaction, a well established research area), and focussed on the activity domain in the product's use phase, but also on the physical product's mediation and information related to the use activity.

Nielsen points out that separate focus (by scenarios, experiments, prototyping) should be devoted to a product's use activity, actions and operations, for understanding the mediation, sequence of operations, existing work practices influences, and to what degree use is as planned or situated. Her research showed, like Mørup's research, our limited abilities to reason from the actual design to its qualities, including usability, unless we put the product in the hands of the user.

9.3. Design for Environment: From Olesen to McAloone

When we entered the design for environment area mid 90'ies, dominated at that time by LCA methodology, idealism and from a design point of view paralysed by the lack of understanding of synthesis, Olesen applied his theories and a group created, supported by Government, a guideline for practical Design for Environment [Olesen et al. 1996]. The basic idea was to identify relations between product- and life phase system characteristics, fig 17, to understand what reason in the meetings and thereby find potential mechanisms for reduction of environmental effects. The mindset creating model, fig 18, shows how reasoning about meetings, product and environmental effects may enhance principal possibilities.

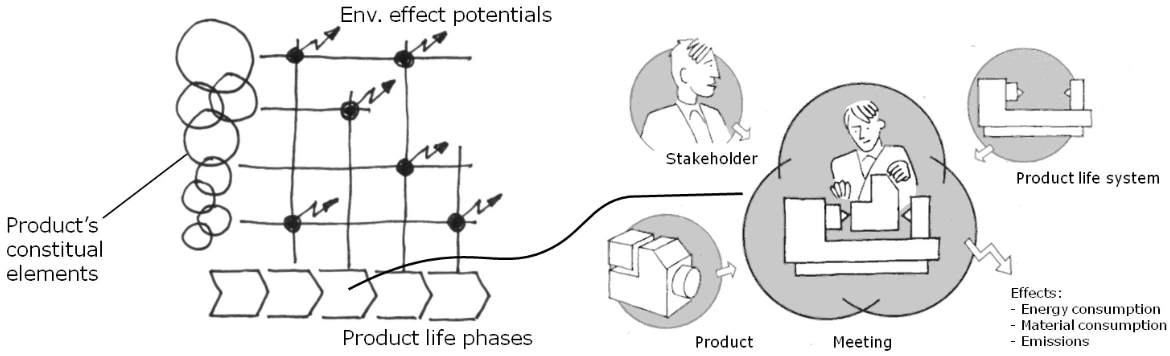

Fig. 17. Environmental effects stem from the meetings and are related to components of the product and life phase activities [Olesen et al. 1996]

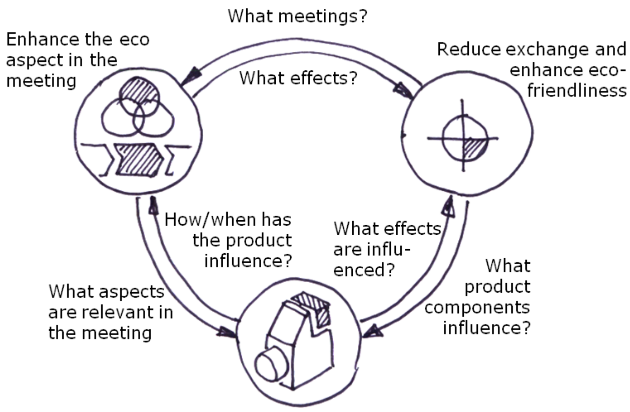

Fig. 18. Mindset model for design for environment [Andreasen 2007] after [Olesen et al. 2006]

The strengths of the philosophy and methods are their fit and balancing against already established procedural and organisational aspects, the pointing out of the need for real, actual, relevant product life insight instead of the normalised, ideal world of LCA, and the power of using visualisation of product life aspects and meetings through gallery technique (and in this way continuing the graphical line from Tjalve).

When Tim McAloone joined our group in 1998 he had defended his thesis at Cranfield on Industrial Application of Environmentally Conscious Design [McAloone 1998]. The insight obtained on timely decisions, early stage focus and tools, the importance of a universal consciousness into a company, - we combined with Olesen's results for a product life-oriented philosophy on our research and teaching.

9.4. From Design for Environment to Product/Service-Systems

Today we focus upon enhanced environmental balancing by deeper understanding of a product's service period, i.e. the period where the product performs its duties and delivers its effects to the user, - but where it also creates damaging environmental effects due to non-ideal use conditions. We identified early research efforts, growing up out of the ecodesign community, aiming at describing and supporting the development of integrated products and services – now better known as Product/Service-Systems (PSS). Our insights into product life thinking, DFX and TTS gave us a running start into the field of PSS research, where we entered in the early 2000's, seeing both the joint effect of product and service – and the delivering company's dual development and delivery of services and products – as systems. We believe that the reasons for PSS emerging from the ecodesign community were threefold: a focus on environmentally-driven dematerialisation in the 90'ies; a well established competence for, and interest in understanding functionality (functional unit), rather than mere physical artefacts; and the experience from working with a complex DFX issue such as environment, stretching over multiple product lives.

The PSS research in our group includes, but is not limited to environmental concerns. Our research in this field encompasses a new and systemic view of the roles of engineering design and product development to support the delivery of functionality – thereby striving to come as close as possible to satisfying customer-perceived value. Our research so far has convinced us that the behaviour of services and products in the use phases of the product's life are identical! Using Hubka's transformation system model we see the possibility to identify product and service layers in each life phase, where products and services create joint effects, fig. 19. Surprisingly our efforts to understand a service's value for the user and its business relations to the supplier give us valuable insight into the same aspects for the product, for early design considerations.

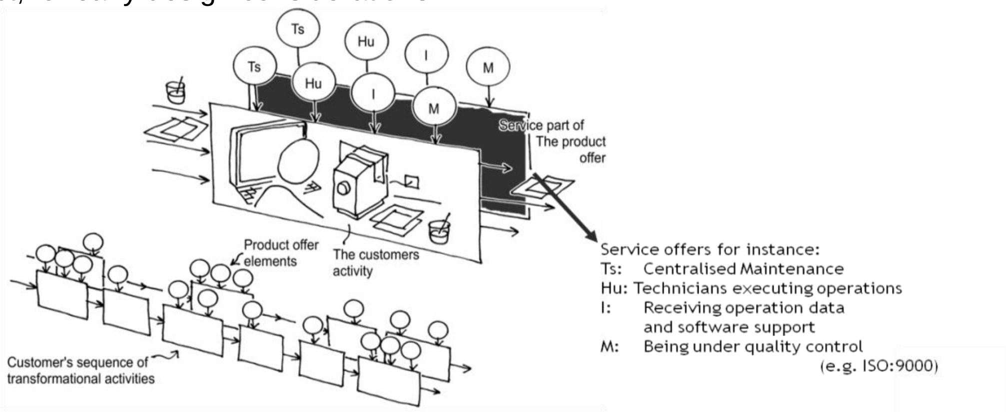

Fig 19. Service only exists, when the customer uses it in one of his activities related to a product. Service is in itself a transformation system, [Matzen 2005]

10. Modularisation and multi product development

Our entry into the field of structuring products, product families and modularisation was supported by ideal research conditions in the late 90'ies. Professor Asko Riitahuhta from Tampere University and Senior Lecturer Alex Duffy from Stratclyde University joined our group, each for one year, as guest professors, and together with them we established a row of WDK workshops on structuring, leading to understanding of principles, laws, the nature of complexity, the modelling of product families and the nature of modules.

10.1. Engineering of engineering, Miller 2001

Thomas Miller defended his industrial PhD project [Miller 2001] on modular engineering in 2001. He expanded the scope of modularisation to cover a company's artefacts, development activities and design knowledge. By establishing coherent architectures in these dimensions for new development projects, Miller created a foundation for enhanced pre-use and re-use of the company's assets and a sound "engineering of engineering" leading to rationalisation. Reduction of complexity and establishing insight into the effects of modularisations are characteristics of Miller's approach.

Miller's participatory research took place in a company developing complex medical process plants (Novo Nordisk Engineering). He showed how coherence could be established between formalised artefact modularisation, modular engineering and design documentation, and current knowledge structured and kept in accordance with the technical systems, the competences and the design activities.

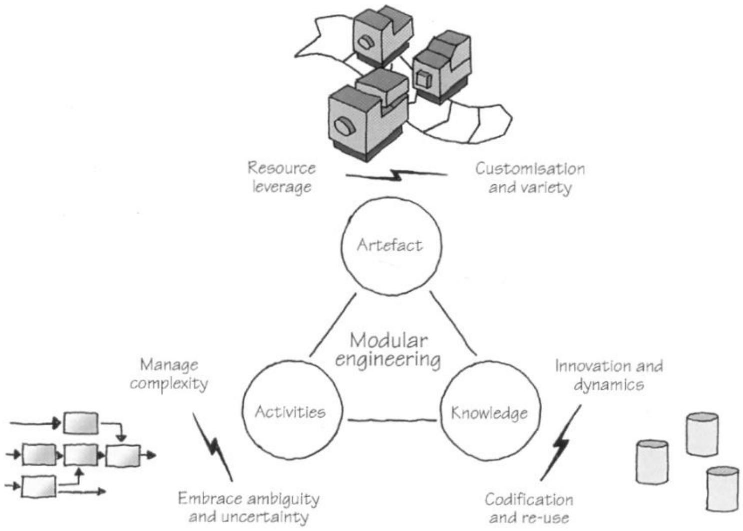

Fig. 20. Miller's focus upon resource leverage, limitation of complexity driven by variety, and optimised customer-oriented variety as effects of modularisation [Miller 2001], redrawn by [Harlou 2006]

Miller's research drew heavily upon TTS and enriched this area with interesting interpretations of a company's need for structuring and formalisation.

10.2. Documented industrial effects, Harlou 2006

Harlou's thesis "Developing product families based on architectures" [Harlou 2006] focused upon creating concrete tools for management of families, in order to harvest the benefits of the application of standard designs (i.e. modules containing designs, knowledge and well known design activities popular speaking) and architecture (i.e. a building principle for a product family), namely reduction of time and applied resources.

Harlou created the theory necessary for defining standard design and architecture, based on TTS and the Domain Theory, seen as three views: *customer view* (features, application activities, properties), *engineering view* (organ structure), and *parts view*. Two tools became central in Harlou's approach, namely *generic organ diagrams*, which are able to show the organ structure of multiple product families, for instance 6 very different loudspeakers from Bang&Olufsen, fig.20, and a *product family master plan* based upon "part of" and "kind of" formalisations.

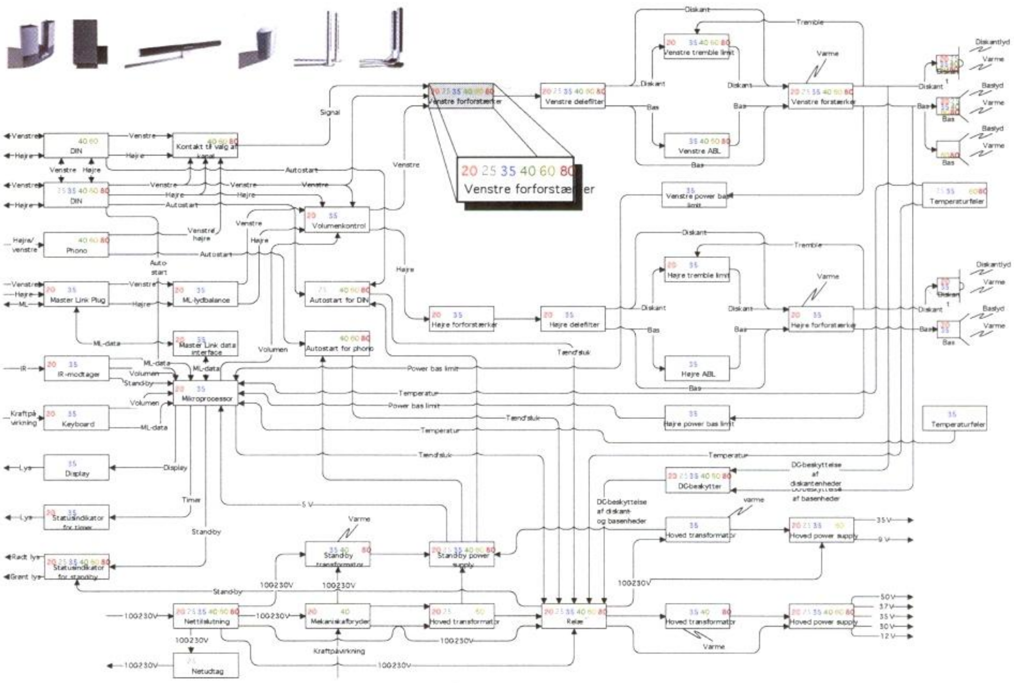

Fig. 21. A generic diagram of the loudspeaker families Beolab 2000, 2500, 3500, 4000, 6000, and 8000 [Harlou 2006]

The two diagrams' abilities to show core functionalities, their use/re-use in different products, and the degree of utilisation of parts for different product variants (and thereby their cost) lead the companies involved to central, powerful management decisions on the development line and the alignment of resources in different functions like purchasing, production, distribution and sales. The research here was based upon participatory research intervention with six advanced industrial companies in Denmark.

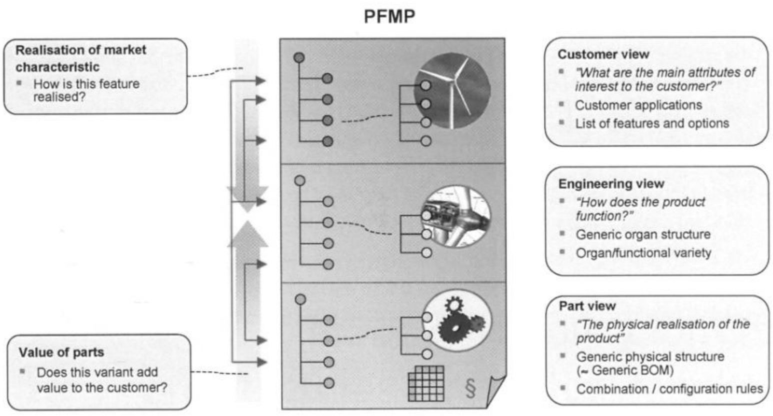

Fig. 22. A product family master plan includes a customer, an engineering and a part view. The views are linked together [Harlou 2006]

10.3. Product customisation, new engineering standards

As a balance of the insight until now into industrial needs and methodical possibilities for creating rational patterns in multi product development, Mortensen has contributed to a textbook on "Product Customisation" [Hvam et al. 2008]. The business process redesign, the modelling of products and their ranges, the product specification processes, and the application of the models for configuration of families and individual products are treated down to practical modelling formalisation details.

11. Starting points and challenges for the future

TTS has always been a means, not a goal, for the group in Copenhagen. In our seemingly planned, but in reality opportunistic – and as far as financing is concerned, chaotic – research efforts we have created substantial research results in the areas mentioned in this article, but we have at the same time created a new version of TTS with substantial applicability and coherence.

A driving force in our current situation is our new generation of teaching, first of all the five year Bachelor-Master engineering programme "Design and Innovation" [McAloone 2007], and the steady open question for research-based education: "What to tell the students?" Our current research efforts in the fields of knowledge management, interaction design, mechatronics, conceptualisation, product architecture, ecodesign and PSS are all founded on an engineering design and product development base, where TSS plays an active role in our internal language and external communication of our view on the nature and characteristics of these research fields.

We see a new world picture of product development, in which the design object has changed over a short historical period from a mechanical system to products understood as technical artefacts, use activities, and symbolic things, to a product life long responsibility of the designer, enriched by services delivered, and designed in a pattern of re-use and pre-use, leading to substantially shorter response times for the companies. All of this should be the contents of the textbooks and the minds of next generation of design engineering students.

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