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60

Kalevi Nevala

Content-based Design Engineering Thinking

In the Search for Approach

JYVÄSKYLÄN YLIOPISTO

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UNIVERSITY OF JYVÄSKYLÄ

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ABSTRACT

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This dissertation is a search for a new approach to real-life design engineering processes. The approach is based on the fact that thinking processes of individual engineers are the central perpetuating force of engineering design. But investigating human mind is very difficult. Main thesis in this dissertation is that approaching thinking through the real content elements could help us to understand design engineering thought processes more thoroughly. The commonly noticed gap between traditional design engineering research methodology and real-life thinking could be filled. Traditional approaches have been mostly intuitive or based on top-down approach from abstract level. A new content-based approach could improve the research and practice of design engineering. The thesis is based on a thorough empirical investigation of a large scale industrial innovation process: the development of Valmet/Metso SymBelt press since 1983. Time span of industrial innovations are long despite the commercial and competition requirements for accelerating the innovation cycles of industry. Investigating a long-lasting design engineering process necessitates reconstructive approach. On-line monitoring is impossible and laboratory scale observations are insufficient for revealing long thinking processes. Reconstructive approach recommended in this dissertation entails reconstruction on three levels: the real change in machines, progression of the plans and interview statements of the participating people. Integration of these three levels provides the empirical material for explaining and interpreting design engineering thinking. This dissertation presents some examples of the empirical data gathered and explanations and interpretations for it. One example of the interpretation is the four mode model of thinking: it starts from a self-consistent mental representation produced by the apperception process and advances through restructuring and reflection to integrating a new consistent mental representation through the constructive mode of thinking. The modes of thinking are not necessarily chronological. They can overlap or are nested within each other. Understanding the true nature of creativity and the organizational dimensions of design engineering thinking are also discussed. This dissertation forms the base for a content-based design analysis.

Keywords: design engineering thinking, content-based design analysis, reconstructive approach to thought research, empirical design research.

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PREFACE

This investigation has grown from my long-term experiences in mechanical engineering design. I have been engaged in the discipline with a varying intensity since 1970; as a practicing design engineer, as a teacher in various positions, as an entrepreneur, and even as an industrial liaison officer at a university. In all these assignments I have been, one way or another, concerned with the meta-levels of engineering design: self-regulation of the designer, project management, customer-based business administration, designer education, scientific aspects of engineering design, normative regulation of design – from the rules of technical drawing up to the plethora of societal directives, etcetera.

I started my postgraduate studies in 1975 under the supervision of Professor Uolevi Konttinen (cited in Paper 2 of this dissertation). However, life took another course. The academic studies were put aside for almost three decades. In the beginning of 2003 I had a possibility to revive the unaccomplished studies thanks to many people mentioned in the Acknowledgements below. This learning process has led thus far to this dissertation.

My reasoning on the motives and objectives of this study has proceeded somewhat like this: throughout my professional history I have felt persistent discomfort with the fact that the methods, which are intended to promote engineering design, do not fit the actual proceedings of the designing engineers. The methods may bring some rigor to certain phases of design work, but eventually the decisive choices are made through "good engineering taste", "common sense" and "intuition". My experiential judgment is that the most crucial problem here is the inadequate understanding of the actual human contribution to the convoluted total process of product development.

During this research process I have found that I have not been alone with my thoughts and doubts. These problems have bothered lots of people around the world. Several recent international contacts agree with my view.

Oulu, Finland
December 19, 2005
Kalevi Nevala

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First of all I want to address my sincere thanks to my teacher and colleague, the late Professor Uolevi Konttinen, who lit the spark in searching for the importance of human role in engineering design. Before his academic career, which he started in 1968, he had led a design engineering department for 30 years; starting it from a drawing office of a couple of designers to en with a research and development department of 350 persons. He knew how engineers think.

Secondly, I would like to thank the supervisors of this dissertation. The collaboration with the main supervisor Pertti Saariluoma, Professor of Cognitive Science at Jyväskylä University, has been unforgettable. His ability to explicate difficult conceptual problems in an intelligible way has inspired me.

The second supervisor Jouko Karhunen, Professor of Machine Design at Oulu University, has supported my efforts in many ways; materially and intellectually. Juhani Niskanen, Professor of Paper Machine Technology at Oulu University, was also among the key persons in initiating this investigation, including the introduction to the empirical case and in recommending the collaboration partners. Laboratory engineer Väinö Vuoto has provided me the practical means for this research. Also, Arja Korhonen and other staff of the Department of Mechanical Engineering of Oulu University have given practical help, without which my work would have been much more difficult.

Professor Pekka Neittaanmäki, the head of COMAS Graduate School of Jyväskylä University has done an incredible effort in supporting and advising me during the final realization of this dissertation. Special thanks also to the editor of this series, Professor Seppo Puuronen, for his valuable counsel in refining the text. Steve Legrand as a language reviewer gave me very valuable advice in producing the final text. Sincere thanks I also deliver to all other staff of Jyväskylä University, who have made this dissertation possible.

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I address my special gratitude to Metso Paper Inc. and all its personnel who have contributed to this dissertation by providing the exceptional possibility to perform a comprehensive empirical study using genuine material.

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Finally I want to thank my wife Ulla and my children Katja and Visa for the incredible support they have given me during the course of accomplishing this belated academic effort. My daughter-in-law Johanna and son-in-law Juha Ryynänen I will also thank for their significant support. Saara and Siiri my grandchildren energized my work in many phases of the writing periods.

LIST OF FIGURES AND TABLES

GLOSSARY OF TERMS

Apperception	Process of integrating representation in mind.
Content-based	Method of searching content elements of thinking.
ENP	Extended nip press for paper and board making machines.
Design engineering	Engineering part of industrial product development.
Extended nip	Extended contact zone for dewatering a wet paper web.
Nip	Contact zone between two rolls.
Paper web	Paper in its various formation stages in paper machine.
Press shoe	Concave beam which makes it possible to extend the pressing zone.
Representation	Expressing something that is not present; in mind or by technical means.

CONTENTS

1 NATURE OF DESIGN ENGINEERING THINKING

Technological innovations obtain their forms through thought processes of the designing engineers. Their contemplations and ideas, expressed in sketches, drawings, written notations and oral communications gradually make product plans real and realizable. Their subjective facilities – explicit, tacit, subconscious or the ones existing on the completely unconscious levels of mind – integrate the new product knowledge in a way we only partially understand. However, one thing is clear; without these mental processes no new technology would be possible and therefore we have to be able to penetrate into the depths of these processes and to scientifically understand this humanely highly important mental work process.

All real design engineering tasks in industrial scale comprise extremely complex networks of prerequisites, requirements, constraints and possibilities. This makes analysis of engineering design very challenging. To manage a product design process one must be able to understand and control all the involved elements and their interactions. If something is missing or miscomprehended risks of faulty design grow. This is why it is necessary to pursue design engineering and its dimensions as a complete scientific conception to the extend that is possible.

There is a common belief that, designing and its complexities are linked only with the elaborate intricacies of the product itself, the organization and the surrounding business environment. This is also the traditional way of thinking design engineering (see Ch 2 for a review). A good description of the contemporary means for coping with the complexities of design engineering is the eminent textbook by Ulrich and Eppinger (2000). In it all the main aspects of product development are carefully explained, but still that picture is an oversimplification, because a crucial source of complexities is missing. As is typical to many other very serious and thorough contemporary textbooks, the designing human minds are set aside (see Ch 2). Of course, the true reason for this omission is that we know relatively little about the mental processes important in design engineering.

There are reasons why we should be able to incorporate knowledge about designing minds in our expositions of design engineering. First of all, the basic unit and the true enigma in engineering design process is an individual engineer. Nothing happens without the contribution of the individual engineering minds. This means that every single idea or transformation of the plan is necessarily channeled through somebody's individual cognitive "machinery", and is thereby subject to the restrictions and intrinsic laws of human mind. Secondly, we have to be able to manage design engineering as a whole; otherwise we cannot make the best out of it. We need to improve the level of creativity of designing in order to answer to the growing needs of customers and to the challenges presented e.g. by decreasing natural resources or increasing complexity of new technologies. Finally, we need knowledge about engineering thinking to eliminate costly and harmful errors. Consequently, we cannot anymore afford setting the mental processes of engineers outside our considerations on industrial design processes.

To make things clearer it is also good to look at the nature of the challenges for the emerging research on real-life engineering design. Let us consider here what engineers must think and what they must know, when they consider real-life mechanical engineering. This makes it much easier to understand the problems and needs of investigating thought processes in design engineering.

Some major topics relevant in professional product development engineering are summarized in Table 1.

TABLE 1 Topics for professional thinking of an industrial product development engineer.

1. ORGANIZATION

Advancing the business of the employer: Needs of the customers; business strategies of the employer; efficiency, costs and impact accuracy of product development; meeting the quality requirements, personal contacts…

Production abilities of the manufacturer: Product assortment; production systems; production facilities; craftsmanship; areas of expertise; production capacity; investment abilities; suppliers and sub-contractors; quality standards, personal contacts…

Product development systems of the company: Product strategies and planning systems; organizational position of product development; internal organization of the product development unit; official and informal position of the designing engineer; professional skills; design expertise areas; design methods and instructions; cost prediction systems; design support systems; facilities; equipment; software; laboratories; test facilities; personal contacts…

2. PRODUCT

Task setting: Strategic new development; total modification of prevailing solution; partial modification; choice from several tested solutions; copying previous solution; ideas over coffee table; personal problem setting…

Function, structure, operation: Purpose function; physical process; process variables; physical structures; machine technical operability; manufacturability; delivery, operation, maintenance, repair for the life cycle; reliability…

continues

continued

Databases: Product specifications; internal standards, norms and instructions; deliverers' specifications; pricing and cost data; handbooks; magazines; patent information; on-line files; research databases; personal contacts to scientists and experts…

3. DESIGNER

Personal professional scientific and technological knowledge: Analytical geometry; differential and integral calculus; numerical methods; vector and matrix calculus; complex analysis; Fourier analysis and Laplace transformation; optimization; probability and statistics; mechanics; vibration mechanics; stress analysis; FEM; material sciences; composite technologies; tribology; nuclear physics; quantum physics; chemistry; measuring techniques; production systems; machining techniques; forming techniques; welding; casting technologies; plastics technologies; tool technologies; fine mechanics; hydraulics; pneumatics; electronics; electrics; bearings; sealing; fittings and tolerances; drawing techniques; CAD/CAM/CAE; managerial skills; personal contacts with different experts…

General scientific and technological knowledge: Beliefs about the universe; limits of human knowledge; history of science and technology; current state of technologies…

General psychological laws: Restricted working memory; focus of thinking; apperception; categorization; selectivity; economy principles of mind; unconscious and subconscious processing; emotions; etc.

Personal qualities and circumstances: Personality; temperament; inclinations; interests; personal experiences; education; professional experience; communication abilities; family conditions; social life…

This list presents some obvious aspects of design engineering utilized in various ways and various contexts in product development. The list may appear rather breathtaking, but all these topics, and more, are present, one way or another, during the course of the professional design engineering process. It is also evident that all these factors are involved and they influence practical design engineering thinking, whether we like it or not, and this is why we simply have to learn to live with them. All of these factors have an effect on thinking of the designing engineers and therefore they should somehow be kept in mind when we consider industrial design processes and the organization of design thinking in them.

In Fig. 1 another way of looking at the required types of knowledge is presented. Diverse kinds of expertise and their interconnections in engineering design can be understood through understanding the diversity of the task environment of individual engineers.

This figure illustrates knowledge networks of an experienced mechanical engineering designer in paper machine industry. The innermost expertise comprises the education of a machine designer, presented in red color in the figure. The domain specific models of thinking are shown by blue color. These educational and experiential knowledge areas are governed by a human cognitive system; in the picture this is exemplified by the theories of Newell and Simon (1972) and the delineations of Saariluoma (1992). This totality can then be seen as a node in the complex network of the task environment.

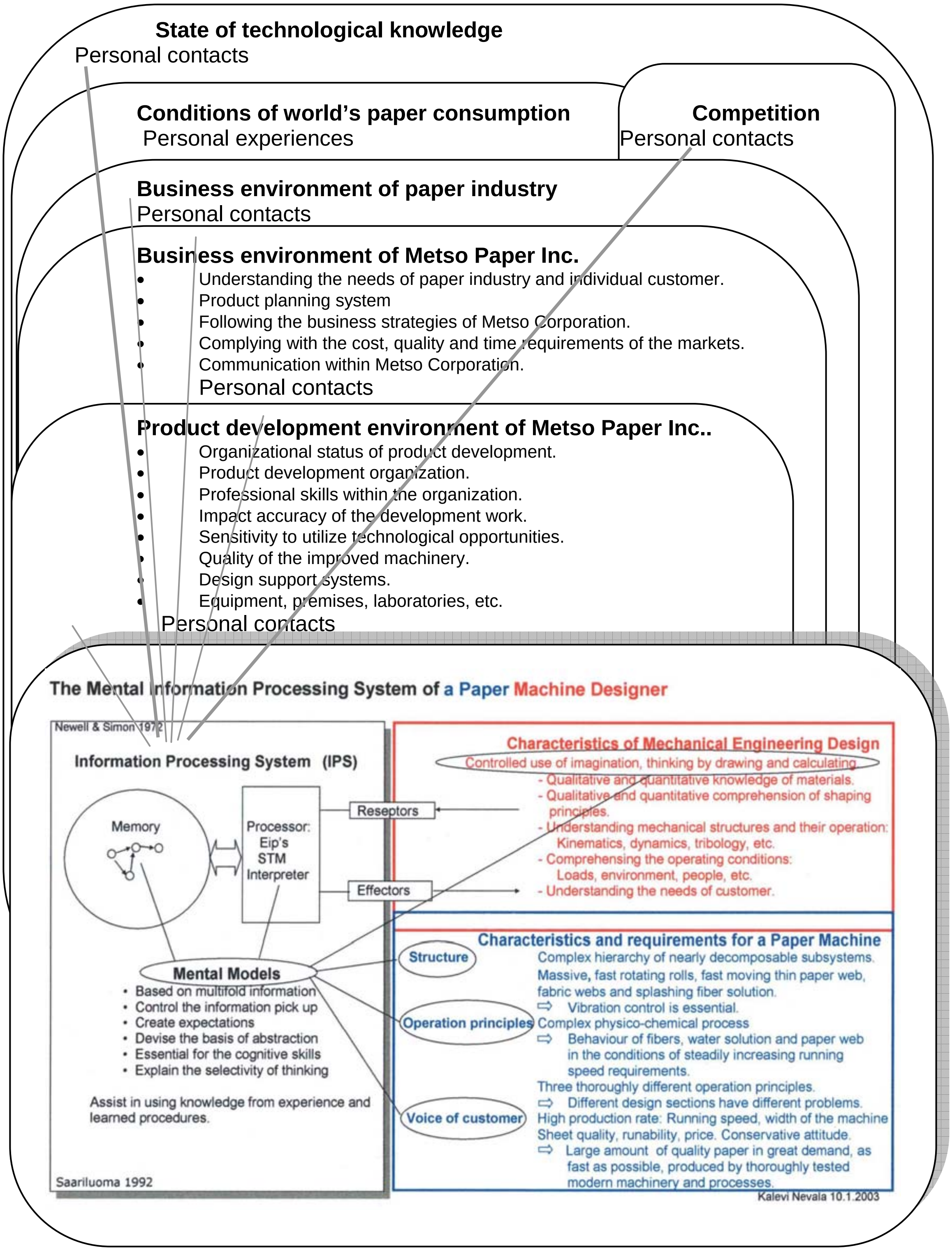


FIGURE 1 An educated engineering mind within the task environment (Kalevi Nevala 10.1.2003)

The complexity of industrial design processes is obvious. Mechanical engineering design, as a discipline, must cover all the planning activities, which are intended for implementing mechanically functioning products – in a rather broad sense. Even though design activities cannot be distinctly extracted from the commercially driven overall venture of an industrial enterprise, there are always certain individuals who are given the task to create bridges from the existing potential possibilities to acknowledged commercial needs. Consequently, the discipline of mechanical engineering design has been split into several classes of expertise depending on the definition of the assignment and the organizational position. Common to all these sub-professions is the capacity of creating consistent knowledge for product implementations.

The total scenery of an engineering design assignment in an industrial setting can thus be envisaged as an extremely complicated set of multifold networks, where human individuals are the decisive intellectual nodes capturing and transforming knowledge in various ways depending on their personal abilities and organizational position; some of them dealing with, and controlling, large totalities and some of them carving the accumulated knowledge into the steel.

2 DESIGN ENGINEERING TRADITIONS

To begin with, the search for an approach it is good to look at some of the major insights of the past. It is good to look at what kind of approaches we have, to consider their strengths and weaknesses and above all to see whether these can satisfactorily cover the requirements of understanding all the aspects of design engineering thinking.

In current tradition of investigating human role in design thinking, three types of approaches have been suggested by Saariluoma and Maarttola (2003). These levels are the intuitive analysis of thinking, normative control and empirical psychological investigation. This division is the staring point. Nevertheless, it seems to me important to add two new types of approach to the list. Thus, discussion includes intuitive, normative, creativity-based and information processing or empirical approaches.

2.1 Intuitive approaches

Intuitive approaches to designers' thinking are based on their own introspective thoughts and other subjective visions about designing. These approaches lack objective control typical to empirical research. For example one of the recent favorite methods TRIZ (Altshuller 1996, 1999, Altshuller and Rubin 1999, Rantanen 2002) is based on a long-period search of patents, but the interpretation of the data is still very intuitive. The objective data of over 40 000 patents is distilled to design rules without proper references to the original sources.

Typical examples of this line of thinking are the traditional ways of applying the engineering sciences. It entails straightforward thinking by the terms of physical and mechanical phenomena on conceptual basis: Various kinds of engineering handbooks, like Kesselring 1954, Shigley and Mitchel 1960/1990, Artobelevsky 1979, 1980 and 1983, or Tekniikan Käsikirja published in Finland in the 1960s describe the intuitively acquired knowledge base of design engineering.

2.2 Normative approaches

Normative design analysis entails mostly engineering experiences about what design should be. Its intention is to provide a comprehensive view about what designers should take into account when designing. The most influential of these directions has undoubtedly been German design science.

From the beginning of the 1960s various systematic design engineering methods were introduced, mostly for the purpose of training new designers more effectively, but also to promote the engineering design practice, e.g. Asimow (1962), Rodenacker (1976), Claussen (1973), Roth (1982), VDI 2221 (1985), VDI 2222 (1977 and 1982), VDI 2225 (1977), Hubka and Eder (1988), Pahl and Beitz (1986), Pahl et al. (2003), Andreasen and Hein 1987, Hundal 1997, Cantamessa (1999), Ulrich and Eppinger (2000), Ullman (2003). In most cases these methods are based on the principles of systems engineering or on the analysis of technical systems. During the last two decades tools for controlling the excessively complex design situation and recognizing better the voice of the customer have also been introduced: Design Structure Matrix, DSM, Quality Function Deployment, QFD and Conjoint Analysis, among others.

The process of engineering design is traditionally described as occurring somewhere outside the contributing people. There an individual engineer is normally understood only as one external component of the design engineering process. Or, as in modern project managing systems, even a potential disturbance of the process. This externalized view inflicts a severe loss of essential characteristics of the real design engineering process.

Another major procedural problem in design engineering is the gap between generalized abstractions and domain specific pre-existing facts. One of the central tools of systematic methods in mechanical engineering design is the technique of abstracting the requested operational behaviors of the planned equipment. It is called functional decomposition of the problem.

Functional decomposition of existing engineering products was introduced by the invention of value analysis and engineering, which was triggered by the severe shortage of engineering materials during last world war. New alternative functional solutions were sought after: the existing mechanical equipments were analyzed by decomposing them into functional elements instead of physical components (Miles 1972). By this method many profound savings and new mechanical realizations were found.

Later on, during 1950s through 1970s, in confluence with systems engineering, the developers of systematic mechanical engineering design methods acquired the function decomposition principle. Now however, for decomposing the requirement structures instead of existing machines (the seminal example is Pahl and Beitz 1986; Beitz was a systems engineer).

The justification for the functional decomposition of required operations was that by this way all possible physical realizations of these functions could be taken into account. Secondly, the functional view was supposed to focus the design efforts on essential aspects of the required operation, like value analysis had shown.

However, common experiences and some findings of this investigation imply that it is very difficult to implement the above described methods into human thinking. There is a substantial gap existing between the idealized procedures and real thought processes. When considering, for example, what happens to the wet paper web in a paper machine's press unit, an experienced engineer does not think by abstracted terms like operator (press nip) and operand (paper web) (cf. Hubka and Eder 1988), or analyze the abstracted functions like support, move, apply force, transform, etc. (e.g. Rodenacker 1976, Pahl and Beitz 1986, Pahl et al. 2003). In a real design situation engineers think by the real content elements of the physical process: mechanical and chemical behavior of cellulose fibers, viscosity of water in different chemical solutions and temperatures, running speed of the paper web through the press nip, geometry of water removal, mechanical properties of the needed equipment, like load conditions, friction, deflection compensation, etc.

Traditional intuitively constructed systematic product development methods are intended to improve engineering productivity, but the gap between them and real engineering thinking is a problem which needs intense scientific attention.

2.3 Promotion of creativity

A quite different perspective to engineers' thinking is provided by creativity research and methods. They concentrate on human aspects of design and work to improve them.

Alex Osborn (1963) is the grand old man of the commercially distributed American methods of promoting creativity in industrial thinking; e.g. Brainstorming and Synectics. He worked since mid fifties with William Gordon (1961), Parnes (1967) and Prince (1970). Weisberg (1986) has criticized this line of thinking.

The promotion of creativity is undoubtedly also directed in advancing engineering thinking. The key idea behind these kinds of methods is bypassing the restricted capacity of human cognitive functions; freeing thoughts. These methods have been quite successful in appropriate cases, but they lack sound scientific basis. Like the intuitively constructed systematic methods also the methods of promoting creativity are mainly based on intuitive ideas. Furthermore, experience has proved that excessive production of new ideas leads to overflow: rational evaluation of all possible ideas and their combinations is very difficult, if not impossible.

The crucial characteristics of human mind in this context is its economy; the intelligent selectivity in focusing the domain specific thinking. Experienced engineers do not have to search blindly through all possible alternatives, they know where to concentrate and what to do without much conscious effort.

Systematic methods and creativity improvement can only be used as indirect tools in organizing design engineering thinking. This is why a trained engineering mind does not find much use for them (cf. for example Tuomaala 1999 and many findings of this investigation). Experienced engineers more willingly follow their experiential intuition. The inbuilt experiential memory structures operate as guidelines for the intelligent selectivity of engineering thinking. Any additional procedure is experienced as an extra burden. This, of course, carries with it the danger of sticking too firmly to the traditions. Productive balance between established traditions and innovative breakthroughs is indeed the key for successful industrial business planning and product development.

2.4 Information processing

Another way of looking at these problems was initiated within cognitive psychology and cognitive science (Simon 1969/1996). It is characterized by empirical psychological analysis of design behavior and designers' information processing (Visser 2003, Saariluoma 2003, Cantamessa 2003, Eckert et al. 2005).

The research of modern cognitive science was initiated at the same time as the development of the systematic design engineering methods in 1950s. A good overview of this history is given for example in Bechtel & Graham (1999), Eysenck and Keane (2001) and Saariluoma, et al. (2001) or Smith (1990). Allen Newell's and Herbert A. Simon's research on the psychology of human problem solving started in the mid 1950s (Newell and Simon 1972, Simon 1969/1996). Their work has inspired the research on human cognition in design as well. They presented a general model of an information processing system, which is suitable in explaining the human cognitive processes in problem solving. The historical significance of this model is that it provided the means for simulating human cognitive processes by computational methods. This was accepted by the scientific community with enthusiasm as offering a possibility for investigating functions of human mind by new, and this time unquestionably scientific methods. The development led rather fast to research on artificial intelligence (AI), even though for example Allen Newell did not completely accept the definition of this new branch of science. AI had partial roots also in the earlier theories of Turing (1946) and Cybernetics (Wiener 1948). Despite the obvious limitations of computational methods this line of research has given an important impact to the cognitive psychology (Eysenck and Keane

2001, Keane and Gilhooly 1992), and even to the understanding of the functions of human brain, e.g. the mechanisms of neural networks. Later on, different areas of the research on artificial intelligence have promoted considerably the research on artificial support for engineering design, e.g. knowledge engineering, expert systems, etc.

Substantial amount of research on engineering and architectural design has been performed on the grounds of cognitive science. Among the earliest attempts to recognize the importance of human thinking in engineering design was Gregory (1966). The actual research on design thinking seems to be accelerated since the beginning of 1990s; e.g. Goel and Pirolli (1992), Goel (1995), Finke and al. (1996), Cross et al. (1996), Gero (1990), Gero et al. (2001), Saariluoma & Maarttola (2001). An interesting reconstruction of engineering knowledge attainment is Vincenti (1990).

Architectural design has utilized cognitive science fairly actively during the last decade. A growing interest in the thought research in the field of mechanical engineering design has also been witnessed: e.g. Nigel Gross and Vinod Goel above, David Ullman et al. (1996), Ullman et al. (1997), Ullman (2003), several proceedings of ICED and ASME Conferences, recent Design 2004 conference on expert designers in Dubrovnik, First International Conference on Design Computing and Cognition 19-21 July 2004, International Workshop on studying Designers 17-18 October 2005 in Aix-en-Provence.

An interesting detail in this history is that the grand old man of the systematic engineering design methodology, professor emeritus Gerhard Pahl, with his colleagues in Darmstadt, Munich and Berlin, has collaborated actively with psychologists of University of Bamberg during the last decade (Pahl et al. 1999). Also other important figures of scientific design engineering research Vladimir Hubka and W. Ernst Eder have emphasized the "Bedeutung des Konstrukteurs" from the beginning (Hubka 1976).

The most recent accounts highly relevant to this research have been the proceedings on the Human Behaviour in Design in Munich, March 2003, the Design Thinking Research Symposium 6 in Sydney, Australia in November 2003 and International Workshop on Studying Designers '05. The proceedings from the first one are published as a book (Lindemann 2003).

3 THE NEED FOR A NEW APPROACH

It is easy to understand that thinking is in the decisive role in a design undertaking, but coming to grips with the actual mental processes is a difficult task. Thought research tries to cope with rather intangible phenomena. One central problem is the indirect nature of human knowledge acquisition and processing. We cannot comprehensively monitor even our own mental activities; large parts of these are beyond any conscious control; and to the mental actions of other people we have access only through the behavioral and other external output from the processes involved.

Research on human mental phenomena was a matter of speculative philosophical reasoning up to the nineteenth century until the emergence of experimental psychology (Aristotle 350 B.C.E., Descartes 1641/1901, Locke 1689/1984, Leibniz 1704/1980, and Kant 1787/1906). But even the progression of the scientifically oriented psychology since the latter part of nineteenth century has been quite cumbersome (Boring 1957, or Wozniak 1995). A dominating doctrine after another has displaced previous ones, e.g. Associationism, Gestalt psychology, Behaviorism, Cognitivism, etc. An all-embracing consensus seems to be still far away. Scientific investigation of mental phenomena is still a subject of unresolved dispute among psychologists and cognitive scientists. Therefore, it is quite understandable that researchers in engineering fields have not managed to form very comprehensive approaches into the rich and lively details of the actual thought processes of the designing engineers.

This fact has caused a procedural drift in design engineering research. The attempts of finding a right approach in investigating engineering design have been floating between diverse set of paradigms. Very good examples of this are provided by the proceedings of ICED in 1997, which discusses rather extensively the alternative paradigms of design engineering research (e.g. Coleman et al. 1997, Eekels 1997, Eide 1997, Gómez-Senenet et al. 1997, Haapasalo et al. 1997, Mortensen 1997, Perrin 1997, Ullman et al. 1997, Wiegers and Knoop 1997), and even the discussions in ICED 03 (e.g. Frise et al. 2003), or several ASME conferences (e.g. Dong and Whitney 2001, Haselrigg 2003) or many articles in professional magazines discussing the obscurity of product development processes (e.g., Goldschmidt 1997, Chen 1999, Bashir and Thomson 1999, Badge-Schaub and Frankenberger 1999, Aoussat et al. 2000 Redelinhuis 2000, Carcia and Calantone 2002, Bertola and Teixeira 2003, Ball et al. 2003, etc.).

The major problems in earlier attempts seem to have been the indirect procedural guidance of engineering thinking, lack of domain specific information and the gap between functional, structural and process levels.

Unlike the traditional process centered view – or other ways of focusing on the design process – the central guideline of this investigation is to bring forward a human centered view on the design engineering process. The constitutive idea is that the contributing individual humans are the only active agents in design engineering process. Design process occurs in the minds of the participating humans. The process doesn't live without human contribution. The external material which indicates the proceeding and progress of the process constitutes only means for supporting and organizing the core processes of engineering design; the thought processes of contributing individuals.

In order to understand better the human role in design it is necessary to search for new approaches. The points presented above should make it evident that it is necessary to investigate mental processes during design engineering. Also the complexity of this challenge should be clear. Hence, it is easy to understand the emerging scientific problems related to cognition: how can we study the mind and thinking of these people? How can we understand them in the best way possible and be able thus foster their work? Obviously, we need a systematic way of answering these questions. We need a new approach.

4 THE CASE

In order to elucidate the role of the engineers responsible for different stages of an important industrial innovation we have performed a rather large scale investigation. We have had a unique possibility of interviewing engineers who have contributed centrally to an important industrial innovation; the development of the so called extended nip press, ENP[1], for paper and board making machines.

4.1 Paper machine manufacturer Metso Paper Inc.

The target organization of this investigation is Metso Paper Inc. and this review is based on the Annual Report of Metso Corporation (Metso 2004). Metso Paper comprises one of the three main business areas of Metso Corporation, which is a result of several company rearrangements in 1999. The other two areas of Metso are Metso Minerals and Metso Automation. In addition, Metso Corporation includes several smaller units under the name Metso Ventures: Metso Panelboard, Metso Drives, Metso Powdermet and Valmet Automotive. The net sales of the whole Corporation were 3,976 billion euros in 2004, and Metso Paper made a turnover of 1,559 billion.

According to the Annual Report 2004 of Metso Corporation, Metso Paper was the global market leader in many products for pulp and paper industries. Its strength is the extensive base of installed machinery. Some 1 500 paper machines delivered by Metso Paper (and its predecessors) are in operation around the world. Metso Paper has also delivered machinery, equipment and

1 ENP was a trademark registered by Beloit Corporation representing then solely the so called open belt extended nip press introduced by Beloit in 1981, but in this text the abbreviation is used in its general meaning and especially to refer to the technical solution of the closed roll extended nip press configuration of Valmet/Metso: SymBelt press by its trade name.

process sections for about 800 pulping lines. Together with Metso Automation Metso Paper can offer its customers a unique combination of process expertise.

Metso Corporation states as its vision to grow from a machine supplier into a provider of competitiveness for its customers. It aims to be globally leading developer and provider of equipment, solutions and services for the customer industries. The interest in partnership throughout the whole life cycle of the customer process is increasing. The most significant competitors of Metso Paper are Voith Paper from Germany, Andritz from Austria, Kvaerner Pulping from Norway and Mitsubishi from Japan.

Today the operations of Metso Paper are divided into four business lines, namely Fiber, Paper, Tissue and Board. The customers are globally operating pulp, paper, tissue and board makers. Metso Paper has its own operations and production in 29 countries, and its products are sold by 25 sales units, more than 40 service centers and the logistic centers in Finland, the USA and China.

The focus of this investigation is on the paper machine business line of Metso Paper Inc. The headquarters and the central production facilities and other business operations for paper machines are situated at Rautpohja Works in Jyväskylä, Finland, where the empirical investigation was also performed.

The last few years have been rather difficult for the paper machine producers. The new investments of paper industry in Europe and USA have been low. Consequently the focus has been on paper machine rebuilds, customer's process improvements and service businesses. For new investments the most promising areas are Asia and South America.

The current strengths of the business, the market leadership, the ability to adapt the new strategy of focusing more on rebuilding and improving customer processes, as well as the strength of competing in new market areas in Asia and South America, and the capabilities of offering the life-cycle partnership to the customers are products of long-term engineering thinking and strategic decisions. The focus area of this investigation, the development of the technologies of wet pressing within last two decades is an impressive example of the long term efforts of building competence. For its major parts Metso Paper Inc. consists of the former Valmet Paper Machinery Inc. In 1999 Valmet and Rauma, both listed companies, were fused to form the Metso Corporation.

The vision and the strategies of an industrial enterprise direct the development of an organization culture and thus frame necessarily the engineering thinking within the organization. In this investigation we follow the development of the organizational culture through the statements and documents provided by five individuals, who were centrally involved with the target process.

4.2 Paper machine

Paper machine is only one part of the papermaking line in a paper factory. However, it is the most noticeable part of the whole line. It comprises a huge complex of rotating machinery, pumps, pipe work, driving systems and control equipment. It is composed of hundreds of thousands separate parts and components. Its total weight is around five thousand tons. The whole papermaking line can be several hundreds of meters long – the paper machine itself measuring over hundred meters. Figure 2 illustrates the structure of a paper machine.

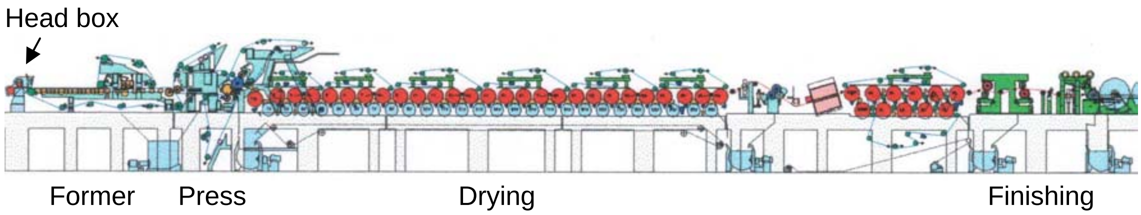


FIGURE 2 Sections of a paper machine (source Metso Paper Inc., edited by Kalevi Nevala)

All this is put together for the purpose of removing water from a liquid solution of about 1 % fiber content in order to form a paper web, which has an optimal moisture percentage for further processing; and meanwhile the web conveyed over a distance of hundred meters with a speed of nearly 30 m/sec.

Water removal is performed basically in three phases: (1) draining (like pouring through a sieve) with the help of suction and centrifugal forces in the former section, (2) pressing (somewhat like squeezing a sponge) in the press section, and (3) vaporizing on heated cylinders in the drying section. All this is done in few seconds.

When the dry content is raised to about 20 percent on the former, the fibers are linked together to form the paper web. The web, for example of news print paper, is about 0,07 mm thick and about 10 meters wide. The paper web is thin and light; the machinery is massive and heavy with surfaces finished by the methods of highest fine mechanics. The hustle and the noise of a running paper machine are enormous.

These extreme proportions of measures and the diversity of the structure and operations are quite hard to grasp by a human mind. How do then the experienced designers perceive the object of their work? Some answers are given below.

4.3 Extended nip press (ENP)

The focus of this dissertation is on one of the most successful innovations in improving the press section of paper machines at Valmet Paper Machines co. / Metso Paper Inc. 1983 – 2003. The following text is a brief review of the interviews and other material of this investigation.

The innovation referred to is the core development of the SymBelt Press configuration. It is in essence a closed roll extended nip press (ENP). The principle is illustrated in Figure 3.

ENP provides a wider contact zone (i.e. the press nip) between two rolls and consequently a longer press impulse on the fast running paper. The lower roll has a flexible mantle, which is pressed by the upper roll against a contoured "press shoe" inside the lower roll. In practical realizations, especially in Sympress B this configuration can be upside down and inclined in appropriate directions.

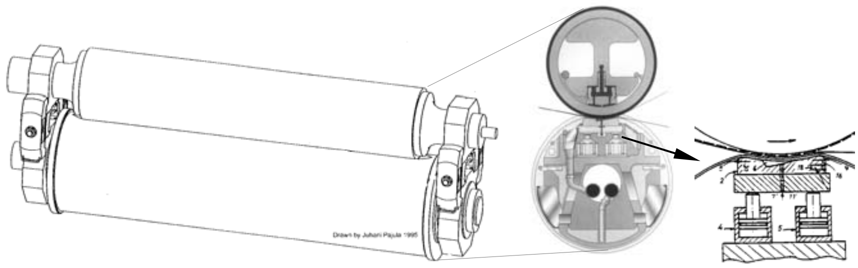


FIGURE 3 Principle of an extended nip press (ENP) for Valmet/Metso paper machines. (Source: Publication of the 10th Valmet Paper Machine Days (1996) and the Finnish patent application no. 963702/3.8.1995; reprinted by the permission of Metso Paper Inc. and the inventor, edited by Kalevi Nevala)

The idea of an extended press zone in the dewatering presses of board and paper making machines is old (see for example patent publications; : (Canadian Patent 452,230, US Patent 3,808,096, Offentlegungsschrift 2108423 Deutches Petentamt). Actually, it is a very natural proposal in order to increase the press impulse for better water removal.

However, there have been many obstacles on the way of utilizing the idea. The problems have been mainly techno-economical facts and beliefs. First of all, up to the end of 1970s the technology was lacking – or was believed to be lacking – reliable means to flexibly support the wet paper web through the extended nip zone. Furthermore, the extended nip zone requires much higher total pressing force, which was thought to require uneconomically robust structures. Maybe the most significant hindrance has been the lack of knowledge about the actual phenomena of the dewatering process in the press nip. The true benefits of ENP – especially for thin paper grades and fast machines – were so uncertain that serious efforts of developing the concept were not undertaken until the late 1970s. An additional reason for the shallow interest in advancing this innovation was the excessive "patent jungle"; for example the German Escher Wyss GmbH had in the beginning of 1980s alone over 700 patents concerning ENP, and the East German originated patent (Fig. 4) from the year 1972 was judged, for example by the experts of Valmet, to restrict the commercial use of the concept so severely that all efforts were suspended.

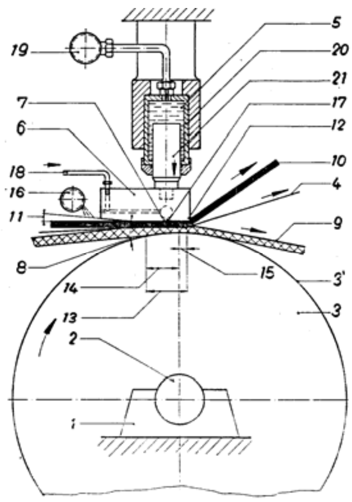


FIGURE 4 Wet-press for dewatering a fiber web. Press shoe (6), flexible belt (10), fiber web (4), press felt (9), extended press zone (13). Source patent publication Germany (1972).

The culmination point of the history of ENP was the delivery of the first production scale open belt "shoe press" (Fig. 5) for a board making machine in Springfield, USA 1981 by Beloit Corporation (USA). This breakthrough was a joint venture of Beloit and the belt producer Albany, and it alerted the other paper and board machine producers. This is the starting point of our inquiry.

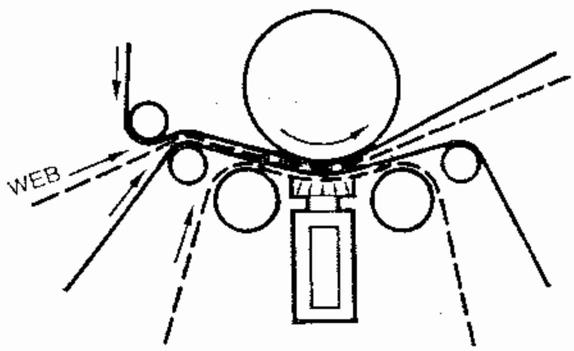


FIGURE 5 The principle of an open belt extended nip press (ENP). (Justus and Cronin 1982).

From the year 1983 onwards, as a part of larger development efforts for new paper machine press concepts, serious investigations of the possibilities of ENP were initiated by Valmet Paper Machines (see table 3 below in paragraph 6.5).

A series of press simulation tests were performed together with collaboration partners.

Concurrently certain key persons began to study the concept through patent publications, professional journals and by visiting sites of the new installations. Results of tests and literature studies were so promising that a pilot machine version of an open shoe press was installed at Valmet 1983. The conclusion from the pilot tests was that ENP gives advantages in producing thick board grades, but in thin paper grades and fast running machines the benefits were judged still rather doubtful; however, it was thought probable that stiff but light fine paper grades would profit from longer but lighter press impulse.

At that time Valmet focused solely on paper machines. Consequently, in accordance with the results of pilot tests, the ENP concept for paper machine press units was postponed. However, almost at the same time the product assortment was expanded also to include board machines, and by 1987 a serious effort to develop an ENP unit for board machines was initiated.

The basic work for designing and fine-tuning the press shoe construction and the sliding conditions between the flexible belt and press shoe was performed with the open belt ENP pilot version, which Valmet had earlier developed. This enabled easy measuring and reassembling means. The eventual goal was a closed roll type ENP (Fig. 3), because the inevitable spraying-off of lubricant oil from the open belt ENP assembly was considered intolerable for the paper and board producing environment.

The eventual outcome of the development efforts was the delivery of the first Valmet ENP press for a board machine by 1990.

From the beginning of the 1990s the concept of ENP was further developed for Valmet paper machines so that the first delivery of SymBelt press for a fine paper machine was accomplished by 1996 and for a high speed paper machine in 1999. By the year 2002 the SymBelt concept was introduced as OptiDwell Shoe Calander for paper finishing.

Today most new paper machines and practically all renovations of press sections delivered by Metso Paper Inc. are equipped with an extended nip SymBelt press.

4.4 Scope of mechanical engineering in paper machine design

From the viewpoint of machine technology the core of paper machine is the press section. The head box is merely a container. However, it performs many essential process functions in homogenizing and distributing the 99% liquid solution of fibers in a desired form into the web former section. The former section, for its part, is composed of rather light machine technology for the main purpose of very fast water removal by gravity, suction and centrifugal forces, whereas in the press section the still remaining water is forced out by heavy loads between ten meter long massive fast running high-tech rolls. This means extreme mechanical and process conditions, and need for machine technical expertise. Drying section has also its mechanical complexities and for example calander press in the paper finishing section can be described as heavy machinery with fine technical features.

When we add the driving systems, hydraulics, vacuum systems, water removal, fabric changing and other maintenance systems, it is easy to understand that paper machine design entails almost all possible areas of mechanical engineering.

5 CONTENT-BASED ANALYSIS OF THINKING

5.1 Content-based thought analysis in engineering design

In this investigation the approach to the empirical case is based on the principles of content-based thought research (Saariluoma 1990, 1995, 2001, Saariluoma et al. 2005). The fundamental idea is that capacity-based psychological research can not reach the contents of thoughts. When a person is thinking, the available resources are always filled with some kind of conceptual material. In different occasions the contents of thoughts are different. Different conceptual domains have different functional systems, which guide the flow of thoughts. Therefore, it is very important to search for the content-based logic of thoughts in order to understand how human thinking proceeds and reaches its goals.

The very essence of content-based thought analysis is to understand the inbuilt logic of the domain of interest. Conceptual structures of human thinking are designed by experience. Experience grows from apperceptive mental operations. Apperception means knowing what, why, how, where, when and by whom. It is therefore necessary first to analyze and explicate the structures and types of the domain specific knowledge, the involved concepts, their attribute structures and the domain specific characteristics of the rationale for making design decisions. This is not however an easy task.

Professor Pertti Saariluoma has developed theoretical ideas of conceptual analysis of the contents of thinking (e.g. Saariluoma 1982, 1985, 1997, 2002, 2005). He has also applied content-based approach in many economical contexts. In Saariluoma & Marttola 2005 an interesting idea of categorizing the conceptual structures of design knowledge by building design ontologies is discussed.

In design engineering thinking the conceptual networks are content-dependent in such a way that the domain specific functional rules can not be reached by generalized design methods on abstract level. The real contents of the domain-specific knowledge determine the design rationale. Generalization or abstraction is only one tool for organizing thinking processes in engineering design. Ultimately in a design process it is necessary to dive into the domain-specific contents in order to understand the sources of design rationale; the reasons why a particular strategic or design decision has been made, and why certain solution is accepted and another rejected.

5.2 Reconstructive methodology

The time span of the target process of this investigation is over twenty years. The process of the target innovation was launched in 1983, and is still going on. Its major outcomes for board and papermaking have been so far: (1) the first Valmet ENP for a board making machine in 1990, (2) the first Valmet SymBelt press for a fast paper machine in 1996, and (3) the OptiDwell Shoe Calander for paper finishing by Metso Paper Inc. 2003.

The long time span involved means that the only feasible way of trying to track the thought processes of the contributing engineers is reconstruction. This was performed on three levels. First, a reconstructive data about the real hardware level changes in Valmet/Metso paper machines were gathered. Secondly, the progress of the plans for developing the paper machine press section during the period of examination was documented. Thirdly, the information of the hardware and plan level reconstruction was combined with the interview statements of individual engineers in order to get a conception of what really have been thought during the long product development period.

An essential property of this kind of real-life conceptual reconstruction is its exhaustively diverse complexity. There is no sense in trying to construct an all-inclusive model in detail. Within the frames of this dissertation it was possible to put up only a fraction of the total reconstructive model of the conceptual and ontological structures behind Metso SymBelt press. Some aspects are discussed in the dissertation papers, some additional details are put forward in this summary part of the dissertation, but majority of the reconstructive and interpretative work is still to be done during the coming years.

The techniques of data collection were designed for the purpose of building a consistent reconstructive model of the ENP-development process. The ultimate focus was on reconstructing the thinking processes of the key engineers. However, in order to get grip of what actually had been thought during the long-ranging innovation process, the interviews in which the engineers stated their own recollections were supported by all available documented information concerning the process.

In several group interviews, e.g. tracks 2 and 3 of the interview recordings CD, and several written protocols of meetings, e.g. 10.1., 28.1., 7.4., 2.6., 8.9.2003, the whole history of Valmet/Metso Paper Inc. development work on wet pressing 1983 – 2003 was memorized by the participants. In addition, most important events and strategic decisions were recollected, detailed information about the state of global papermaking technologies and company know-how were discussed and the propositions for further improvements were reconciled (see Table 3 below); the best references for further data acquisition were sought after. Organizational data, engineering handbooks, writings in professional magazines, patent publications, etc., which were recommended by the interviewed engineers were gathered. The urgent request of papermaking industries for increasing the paper producing capacity considerably was identified as the major driving force for the creative design engineering processes in paper machine technology since the late 1970s.

Moreover, lots of so called "peripheral details" (cf. Neisser 1976, 1996) were checked out. This kind of information, even though it has no immediate connection with the interview statements, is very important in assessing the total field of knowledge, which constitutes the frames and contents of the domain specific engineering thinking.

For example many details of the history of papermaking, physical details of the paper web formation (e.g. the role of so-called chemical hydrogen bonds between cellulose fibers and water molecules), or the organizational arrangements between Valmet, Tampella and Rauma-Repola which resulted in the founding of Metso Paper Inc. in 1999, and even the sudden bankruptcy of American Beloit Corporation in 1990s which resulted in a global redistribution of paper machine manufacturing business are all examples of the important background information, within which the individual engineers are working. Most parts of this information will never come out in an explicit form. It remains mainly unspoken, but nevertheless, this kind of information is a significant factor in engineering thinking. Insightful understanding of this background information is essential in reconstructing the engineering thought processes.

The interview techniques were carefully surveyed (e.g. de Groot 1965, Wertheimer 1945, Cicourel 1985, Antaki 1988). The interviews were designed to be an unstructured dialogue between experts of paper machine technology. Only the main theme of the interview session was stated. The principles of cognitive interview techniques (compiled e.g. in Eysenck and Keane 2001, cf. also Neisser 1996, or Wertsch 1998) were applied in appropriate extent: (1) the memory marks are supposed to be complex and containing diverse information, (2) what can be recalled from memory depends on the overlap of stored memory marks and the current situational information, (3) diverse kinds of hints in discourse situation can lead to any of the memory marks, therefore, try to use the most effective ones.

Due to the reconstructive approach a crucial characteristic of our interview technique is that the engineers told what they are thinking today about various phases of the long ranging development process. Document analysis was then used to confirm the recollections and for the purpose of guiding researchers' focus.

During the interview sessions the engineers also willingly drew sketches in order to illustrate their ideas at the time when they contemplated the new inventions to the ENP concept. Fig. 6 is one example of these illustrations.

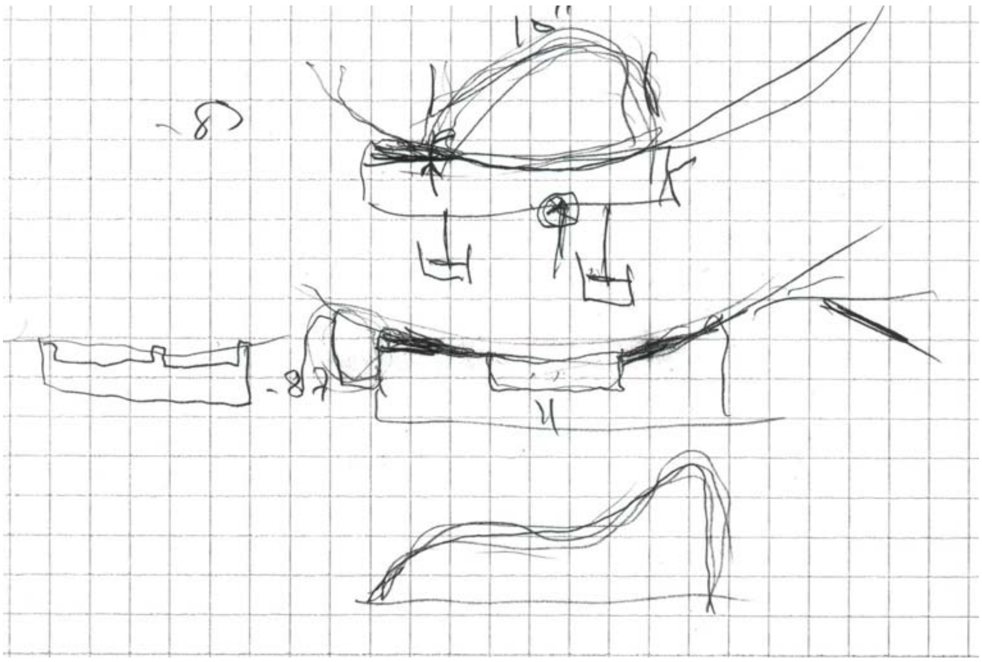


FIGURE 6 An example of the sketches by which the interviewees illustrated the ideas they have had, when designing; in this case the press shoe construction in 1983 and 1987.

6 DISCUSSION: EXAMPLES OF THE CONCEPTUAL LEVELS AND STRUCTURES OF ENP DESIGN

The focus of this inquiry has been on the subjective scenery of several individual engineers who have been committed to advancing an important industrial innovation, which eventually led to Metso SymBelt press configuration discussed above.

All five individually interviewed engineers have a background of a mechanical engineer. Therefore it is not unexpected that their thinking is largely based on pictorial material.

Following examples of the design knowledge in the investigated case are primarily pictorial presentations extracted from our empirical data. These examples are aimed to outline and expose the complicated reality, which is related to ENP development thinking, but the examples are by no means all-inclusive. They comprise only some simplified exemplars of the ontological structures on which the mental conceptualization of thinking of the engineers is based. A proper conceptual analysis is still to be done during coming years.

6.1 Representing the focus of the task

The content elements of the mental representations of designing engineers are based largely on simplified pictorial material. These representations serve as channels for the utilization of whole repertoire of the conceptual professional knowledge which is in the possession of the engineer. Figure 7 illustrates some elements which are involved in this process.

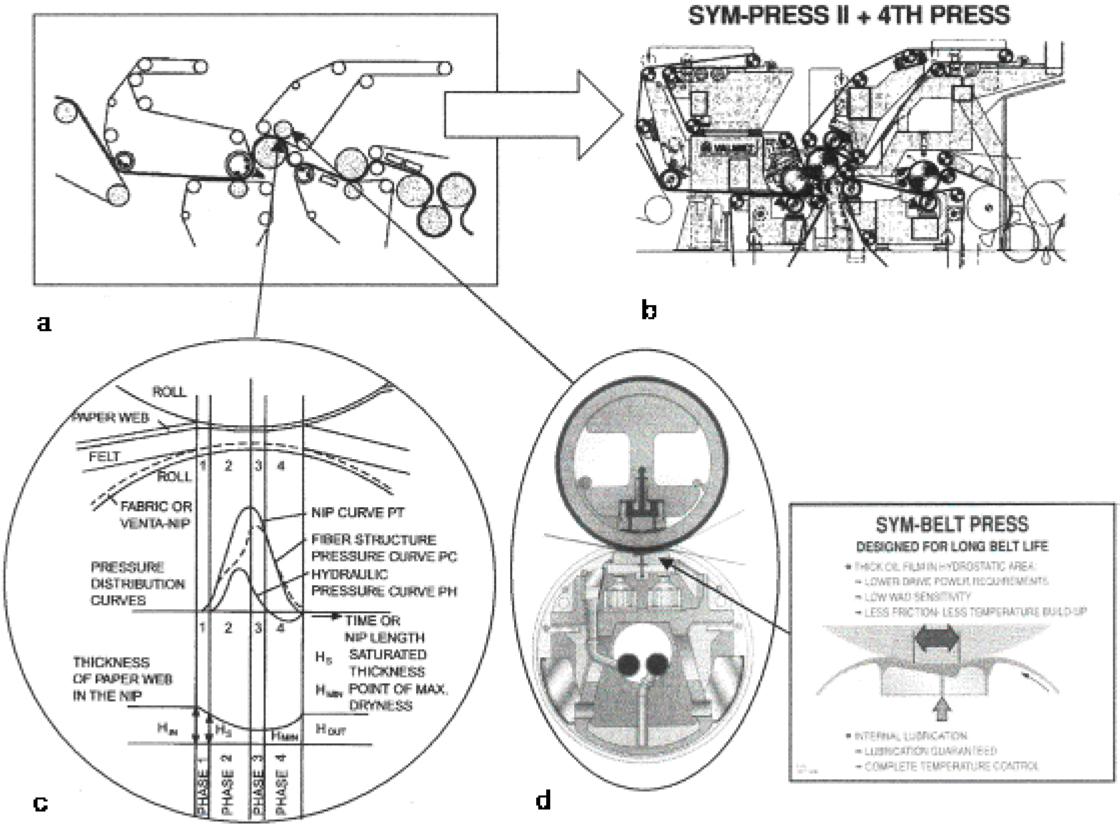


FIGURE 7 Some basic elements behind the mental representations of the ENP designing engineers. (Source Metso Paper Inc., edited by Kalevi Nevala)

Figure (7a) is a typical draft in paper machine design. Thousands of patents have been granted on the basis of these kinds of pictures. The circles and loops have been drawn behind cigarette packages, on serviettes, on drawing boards and computer displays. To a layman this figure does not tell much, but when an experienced designer looks at it, he automatically recalls a huge amount of detailed information about a real Sym-Press II + 4th press (7b and 7c), or he can create visions of new innovative changes to the configuration (7d). Fig. 7 illustrates thinking inwards to the construction.

Another direction of focusing the task representation is to think what kind of a puzzle it is to assemble all the components and subassemblies together. Fig. 8 gives one example of this line of thinking; how to get the subassemblies fit together. "It is like playing chess" was one comment in describing this process. Design engineering thinking on this level is actually combining existing subassemblies into a working machinery.

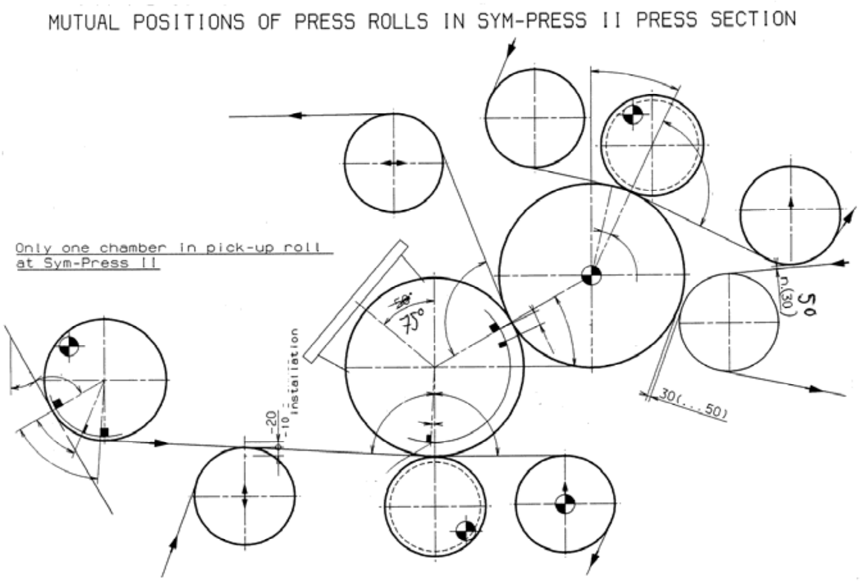


FIGURE 8 Example of functional reasoning in press section configuration. (Source Metso Paper Inc., edited by Kalevi Nevala)

6.2 Comprehending physical process phenomena

The interviews demonstrated unanimously that all engineers had internalized three "umbrella rules" of paper machine design. Three conditions must be fulfilled simultaneously: (1) the grade specific paper quality must be achieved, (2) the runnability of the paper machine must be maximized and (3) the constructs must be machine technically feasible. Otherwise the proposed new solution is not realizable. Noteworthy here is that the first two of these rules of design thinking are customer specific. Machine technology comes only on the third place in the thinking of mechanical engineers. The rules are also a very good example of the importance of the content-based logic within a mutually approved organizational culture, which lays the ground for individual engineering thinking.

These rules show that paper machine thinking of designers and executive managers is primarily directed to the success of the customer process. Achieving good paper quality is the topmost goal. Figure 9 presents some examples of the background knowledge which forms the mental representations related to paper web formation. These figures were suggested as examples by the interviewees.

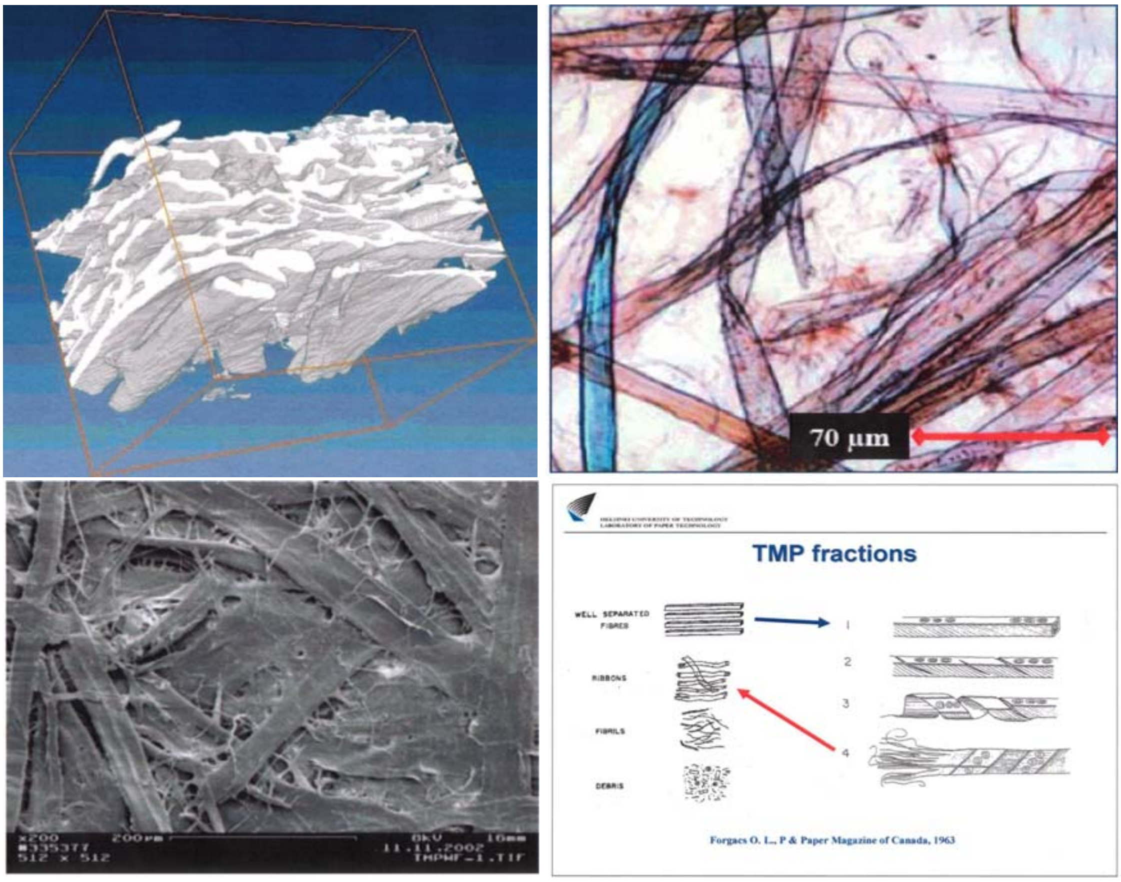


FIGURE 9 Examples how engineers represent the basic principles of the paper web formation. (Source Metso Paper Inc.)

Naturally there is much more knowledge base influencing thinking also on this level, ranging from atom scale hydrogen bonds, through water viscosity to the questions of water removal from the web to the face to face running fabrics. What seems to be important is the apperceptive nature of thinking; all aspects are integrated into a self-consistent mental representation.

6.3 Machine technical level

Fig. 10 below presents in a simplified form the mechanical arrangement of ENP. This is again a figure which triggers a huge amount of professional knowledge in the mind of an expert designer.

Mental representation induced by this picture into a trained mind comprises actually everything that is known by the expert about the ENP. This kind of a picture triggers a holistic mental representation which integrates vast amount of knowledge types, levels and details; from the physical process of water removal from the paper web to various details of the machine construction. Table 2 presents some aspects which were found out during the investigation. Numbers in the table refer to Fig. 10.

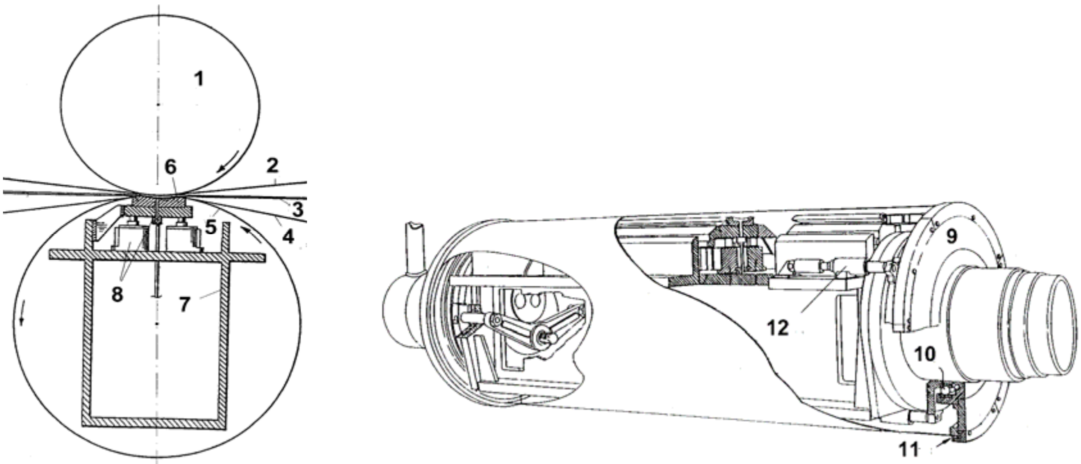


FIGURE 10 The principle of Valmet SymBelt press. (Source Patent publication PCT, WO 91/17308, edited by Kalevi Nevala)

TABLE 2 Examples of the technical design attributes of an ENP unit.

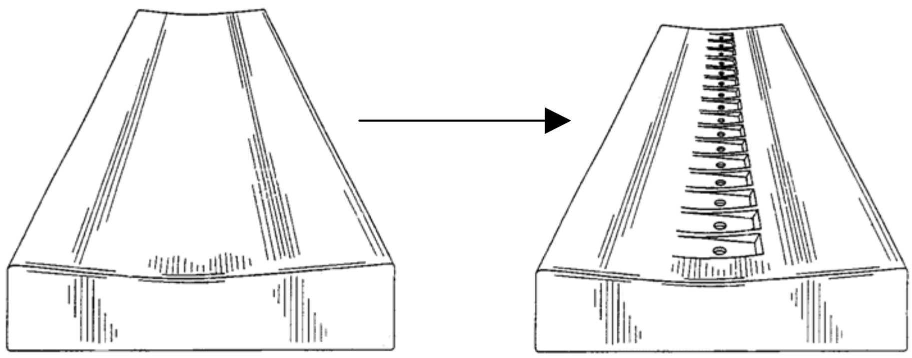
Component	Central technical attributes
1. Counter roll	- Surface properties - Diameter - Length - Deflection compensation - High load carrying capacity
2. and 4. Dewatering felts	- Thickness - Porosity - Fiber qualities - Tension - Initial moisture - Water removal properties - Stability of properties over time
3. Paper web + water	- Requirements for the paper grade - Dewatering process
5. Flexible mantle	- Absolute impermeability - Surface properties - Sliding properties - Flexibility - Resilience - Dimension and form stability - Heat resistance - Endurance - Void volume in the mantle surface to improve water removal
6. Press shoe	- Surface geometry - Surface properties - Lubrication
7. Supporting beam inside the Roll	- High load carrying capacity - Space and placing for cylinders and hydraulic oil feeding and removal equipment
8. Hydraulics	- Loading cylinders and lubrication oil feeding in the shoe - Hydraulic center (not shown in the figure): Loading hydraulics, lubrication hydraulics, oil cleaning and cooling systems

continues

9. Roll end plates	- Minimum weight (The flexible roll is rotated by the counter roll through friction forces, i.e. the flexible mantle drives the end plates)
10. Bearings	- Minimum friction (see above)
11. Mantle-end plate fastening	- Enables the flexible mantle assured fastening without oil leakage - Enables the flexible mantle to be fastened straight
12. Mantle stretching devices	- Enables the flexible mantle to run straight and round

Furthermore, in order to make this assembly a functioning part of larger machinery many other details must have been solved (not included in Fig. 10 or Table 2). There are also equipments for power supply, hydraulics units, the means for applying the pressing force, water removal equipment, the support structures and frames of the press unit, felt changing means, mantle changing means, etc. All of these constructs and arrangements further include a substantial number of fine-grained intricacies. All of them must have been thought out by somebody.

The most essential detail of this construction is the press shoe beam illustrated in Fig 11. And the most essential innovative advancement was the hybrid press shoe with hydrostatic pockets to decrease friction and provide better lubrication (Fig. 11B). This figure crystallizes several years long design engineering thinking process with several sub-solutions and rejected proposals.



A. Starting point
Hydrodynamic press shoe

B. Final design
Hydrodynamic + hydrostatic = hybrid press shoe

FIGURE 11 Example of an innovative change in the press shoe design. (Source US patent 5,997,695)

Finally, in Fig. 12 and 13 the end results of twenty years long engineering thought processes are expressed.

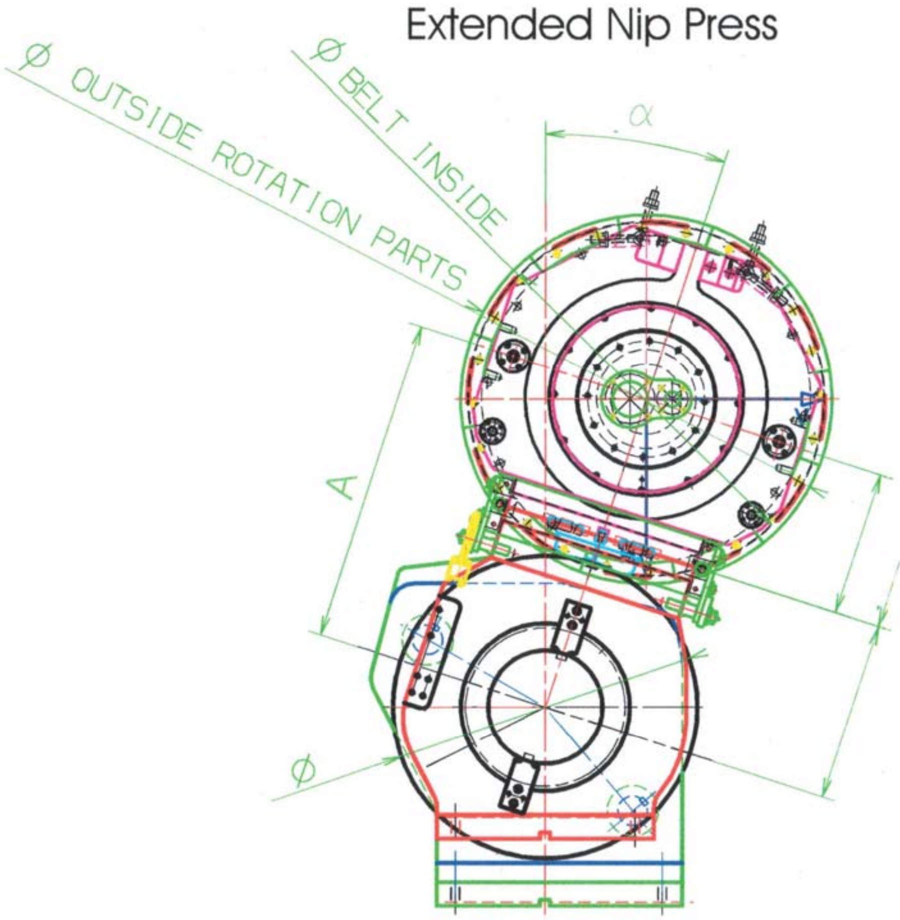
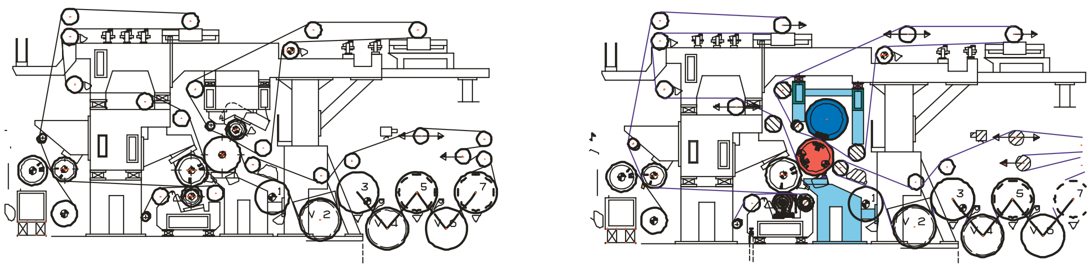


FIGURE 12 Example of a modern machine technical representation of an ENP. (Source Metso Paper Inc., edited by Kalevi Nevala)



1984: SymPress II

2004: SymPress B

FIGURE 13 Example of twenty years development of the press section; a renovation of press section for better efficiency by utilizing ENP. (Source Metso Paper Inc., edited by Kalevi Nevala)

6.4 Functional level

In engineering design such methods as functional decomposition of concrete machine structures or constructing abstract functional structures of the requirements, and morphological analysis of the prospected technical realizations are in use. Fig. 14 illustrates an example of functional decomposition. This figure is one of seven pages exploring the necessary functions of paper machine press section.

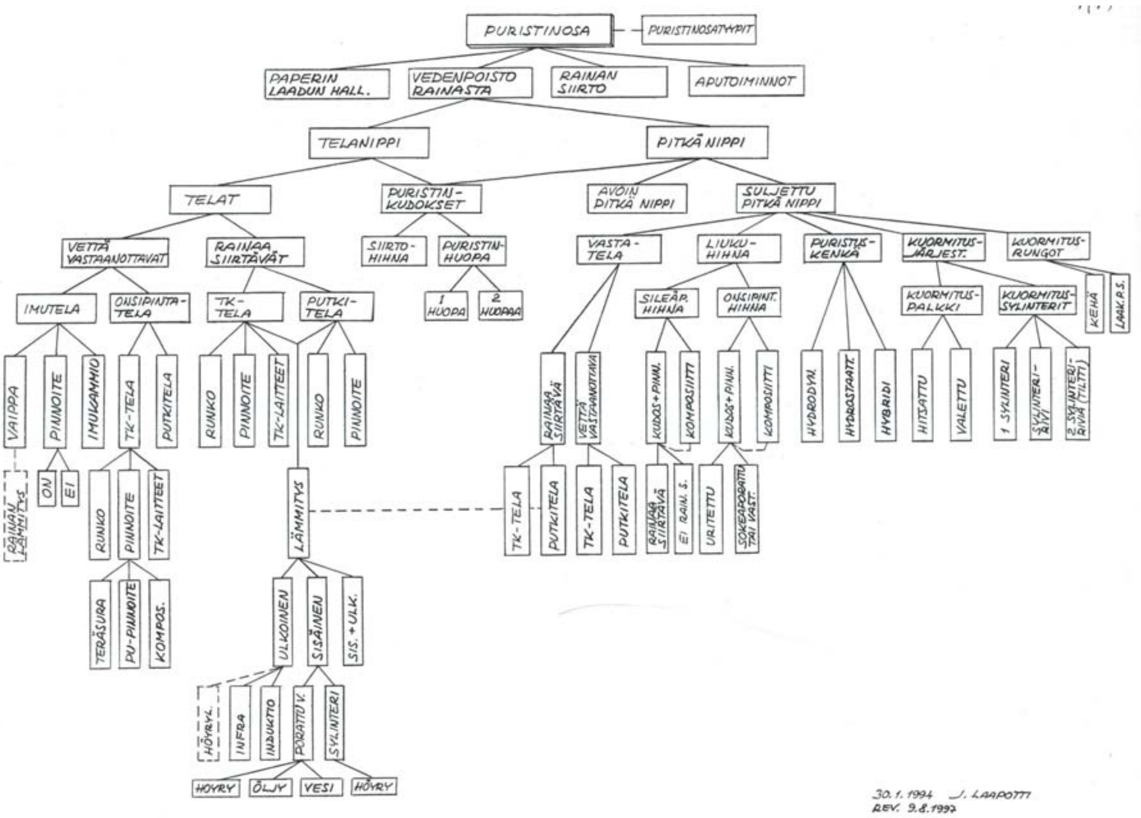


FIGURE 14 Example of functional decomposition of the press section. (Source Jorma Laapotti / Metso Paper Inc.)

Major problem in all methods of analyzing design knowledge seems to be the incompatibility of different abstraction levels. Categorizing is always abstracting and simplifying the reality. It can be done in several ways on different basis. Especially, complicated systems allow seldom straight-forward analysis to mutually exclusive categories. This is certainly true in the context of papermaking.

6.5 Human level

According to our empirical material the fundamental driving force for developing competitiveness of Valmet paper machine press section in late 1970s and in the beginning of 1980s was the customers' unrelenting requests for higher production speed. This request was crystallized by the participant engineers and executives into two central requirements for developing the press section: (1) for higher running speeds a longer press contact was needed in order to accomplish sufficient press impulse for water removal; (2) the so called free-run sections must be eliminated. The first requirement led eventually to the ENP and second to completely closed-run OptiPress concept.

The following quotations from the interview protocols describe the engineering thought processes at that time. Especially the way of thinking in mechanical engineering, i.e. the prerequisites of comprehending mechanical realization requirements and possibilities in developing the press section was in focus.

Question: How is your education as a mechanical engineering designer connected to your current professional identity? (T10: 00,00,48):

> … How would it be connected? A good question, because what I look now for is more like the starting phase of technologies… How is it possible to get new solutions to fit the business; how they fit the organization and everything else…? So the mechanical engineering comes not necessarily first. But it comes unavoidably in some phase when these new things must be integrated to the prevailing "orchestra"… Of course, it is also possible to change procedures: if things don't fit, the orchestra can be changed to a more suitable to advance things. One could say that it is the question of creating new competences… actually, how new competences can be connected here… But mechanical engineering as such… it changes and lives in that respect… Altogether, it is always there on the meta-level.

Explanation: This statement clarifies how the way of thinking in mechanical engineering is connected with the business level strategic thinking. An educated mechanical engineer acquired totally new thought processes, when brought to reflect on the level of the total business activities. Machinery is not the most important thing to bear in mind. However, the machinery it is always necessary in order to accomplish the process.

Q: Do you think by the terms of a machine designer when you handle these things related to business promotion? (T10: 00,02,17):

> Some things I think some I don't. It is not all embracing … More like thinking how this will affect the business of the paper producer. One must outflank rather far in order to get back to these matters…

Q: When you face a new idea, how do you asses its feasibility? Are the economical aspects on top? (T10: 00,02,50):

> … Yes, economical aspects are mixed in that… But it also must be somehow visualized to some kind of a conceptual image… By what kind of equipment this could be done… The process is required, but also the equipment… Normally the equipment causes the costs. In other words, some kind of vision about the "gadget" world is necessary.

Q: What I am actually after is what makes you think that something is possible? (T10: 00,3,27):

> … Normally we say that if the process can be built up, so the engineers will invent the rest… Things that we can get done will be explored … Of course sometimes we meet a situation in which you must simply put your hands up… that it wouldn't appear to be an economical solution.

Q: [During the group interviews, when talking about doubling the speed] you expressed an impressive attitude in stating that there is actually no upper limit for the speed of paper machine. Do you still think so? (T10: 00,04,10):

> Yes, I do… Setbacks of course… Money can run out from time to time… As said, then there come also other hinrances… But as you can see, it hasn't been… there have been opinions that [the speed] is so high that it should not be increased, but always it has been increased… And always [the machine technical] solutions have been found to solve the problems… More problems… economic problems come from other things…

Q: I remember that 33 years ago we thought that there are some physical restrictions… (T10: 00,04.48):

> … of course, the speed of light will come to way… that I believe, but it is so far away that it is not necessary to use this argument in real world.

Explanation: Even though this comment is a half joke, it exposes (in connection with the previous quotations) a very important aspect in thinking of this engineer. The mental space in professional matters is not restricted by conventional technological presuppositions.

Q: Then, could you tell me what are the elements of your professional thinking?... Are they the resources or are they the anticipated new solutions? (T10: 00,05,52):

> … Yes, I certainly think through visual things… So I try somehow to visualize them… to conceive them as figures or gestalts…

Q: I mean… whether your main task is to develop the organization or the products… (T10: 00,06,12):

> … the products – regardless of whether they are services or physical products… That is the way I am looking at the world.

Q: …According to the prevailing strategy the customer process… ?

> … and also if there is need to change the strategies… It is rather unlimited… But I do not much interfere… the resources. They will be decided later… By the engineers. Of course I myself have to intercourse…

(T10: 00,06,50):

> … Specifically, the main task is how in general it is possible to change the paper industry in this world… how to improve its profitability… and get better life to the customer… and through that also better life to us. So, that I look quite far in the terms of the profitability of the paper industries. Such gestalts as… readily, if conceiving papermaking… so there are such totalities as the paper process, energy process, environmental matters, water matters… this kind of totality is whirling all the time in mind… wood material, where there is fiber, where not… like these things must be done in China today. And what is this story of USA, where paper industry is going down… how we can manage there…

Q: … So you have a global view… and responsibility also? (T10: 00,07,45)

> Yes…

Q: If we then will go to the extended nip concept, when was it that you had your first contact with it? (T10: 00,08,46):

> It must have been the literature… actually, like you have been discussing with others we started the press simulation tests with collaboration partners… At that time I was responsible of developing the press section and drying section… at the turn of 1970-80… So, then these matters came from the literature. We started to build test equipment and laboratory scale tests… As discussed before [during the group interviews] it walked to the board side… and what Beloit did in America… We ourselves did not have enough expertise at that time so that we could have started to do something straight for the paper side… We concentrated on the paper machines…
>
> So, from there, and on the other hand, at that time the [paper machine] speed was raised… Actually when I game here in 1979, I joined a project for increasing the speed; there was discussion about so the so-called "closed run" [of the paper web] in the press section. We did it together with partners… Actually the idea came from them… It guided actually us to road of raising the speed… Problems were seen the of increasing the speed…

The quotations above stated comprise only one example of the analysis of interview data. Table 3 below is a distillation of large amount of individual and group interview protocols. It clarifies the content-based logic of Valmet/Metso PM press section development since 1983. It also provides a summation of main alternatives, which were thought by the press section developers during the investigated process.

The engineers who participated in the individual interviews during this investigation were assigned to several decisive positions in advancing these innovative thoughts. The following schedule in Fig. 15 presents the progress of the process and roughly the time periods when each engineer participated in the process.

TABLE 3 Development of press section and ENP 1983 - 2003

Development of Valmet PM press section	Development of ENP unit
SymPress II (Fig. 13) was the prevailing press concept up to 1983. **Press 1983 project** was triggered by the customer feed-back: ”*Make it sure that the next delivery is not SymPress II*” - About fifteen executive level participants, the secretary from product development department. - Many meetings and plenty of ideas. - Controversies in opinions; new executives brought their own ideas. <u>**Several development projects were launched**</u>: - More press nips (SymPress II + 4p). - **Extended nip technology** → - Large roll, soft coating (disadvantages: shear forces caused by the deformation and consequent temperature rise). - Unfastened flexible belt: same dry content can be reached as by extended nip. - Drag-belt (lengthening the press impulse by hysteresis, didn’t work). - Steam-boxes (normally between 1st and 2nd nips, 10% more heating means 2 % in dry content). - Heating of the center roll: adopted from Calander-roll heating system: holes for hot water in cylinder mantle. A couple of rolls were delivered. Disadvantages: paper web sticks on the roll mantle and the needed heating energy for wet paper web is excessive.	**Previously acknowledged idea, which was hindered by many reasons**: - Lack of knowledge about press phenomena - Lack of materials and other technology - Patent jungle, e.g. Escher-Wyss had about 700 patents in 1983 **First open belt ENP delivery**: - Beloit (Munksund, Sweden) 1982 - Engineers from Valmet and Tampella got acquainted with the invention at the site - Beloit had already a culture of producing rolls and partnership with the belt producer Albany (Escher-Wyss was also a roll producer) ↓ **Actions at Valmet**: - The base technologies and materials, the shoe construction, process, and so on, were studied - Press simulation tests with collaboration partners 1984 - Pilot machine version to Valmet 1984. It was an open belt ENP according to Beloit - It was necessary to bypass the patent jungle in designing a new shoe construction - First pilot test maybe too hasty **Result:** - <u>Mechanically functioning, but paper technical advancements were doubtful</u> - Not feasible in paper machines, but cost effective in board making - Through company arrangements Valmet expanded the product selection to board machines

- Impulse drying: e.g. heating the counter roll surface of an extended nip press by induction to 200 - 300˚C, causes new physical events, so far an unresolved method.

- Induction heating of a roll nip was tested and some American tests were reviewed

All contact heating systems have a drawback of lopsidedness of paper web.

<u>The development of the press section proceeds by projects:</u>

Some result in new designs; some tend to continue as "eternity" projects; some are closed.

Escher-Wyss delivered the first closed roll ENP 1985

Tampella tested small arrangements, where the hydraulic fluid was water; "ice shoe"

Development in a daughter company in Sweden:

- The company had their own proposal for extending the nip by a large roll having a flexible hose mantle
- Valmet pilot machine version of ENP was transferred to Sweden
- <u>A closed Belt roll for a board machine was developed; and delivered by 1990</u>

- <u>The hybrid shoe was also developed for this delivery</u>

Later development of ENP:

- First paper machine delivery 1998
- OptiDwell Shoe calander 2002

Difficulties in applying ENP:

- High costs
- Crane capacity of paper factory; Belt roll 80 tons; counter roll 120 tons
- Temperature limit for belt 60 – 80 centigrade
- Endurance of grooved belt
- Water removal from grooved belt is difficult; doctoring must be gentle
- A paper clump can crack the belt

The key question is the endurance of the belt: breakdown is costly

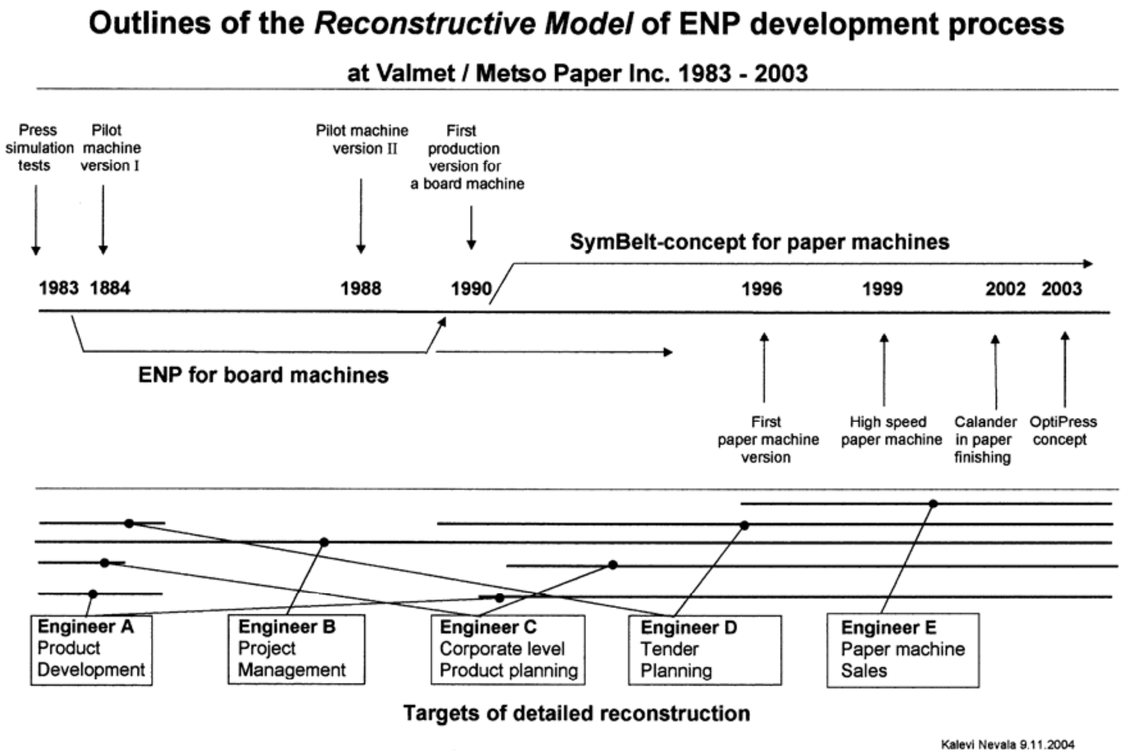


FIGURE 15 Summary of reconstruction of the development of Valmet/Metso SymBelt concept

According to our empirical material mental representations of these engineers about the same process were rather different. The focus and information contents differed according to the assignment and organizational position during the process, which could of course be expected. These findings suggested however that the engineers had created different task definition windows through which they looked at the innovation process. The frames and details of the view were different. These questions are discussed in paper 4.

The analysis of the empirical material revealed an interesting cycle of these windows. Fig. 16 is a simplified illustration of the task definition windows and their interplay discovered in this investigation.

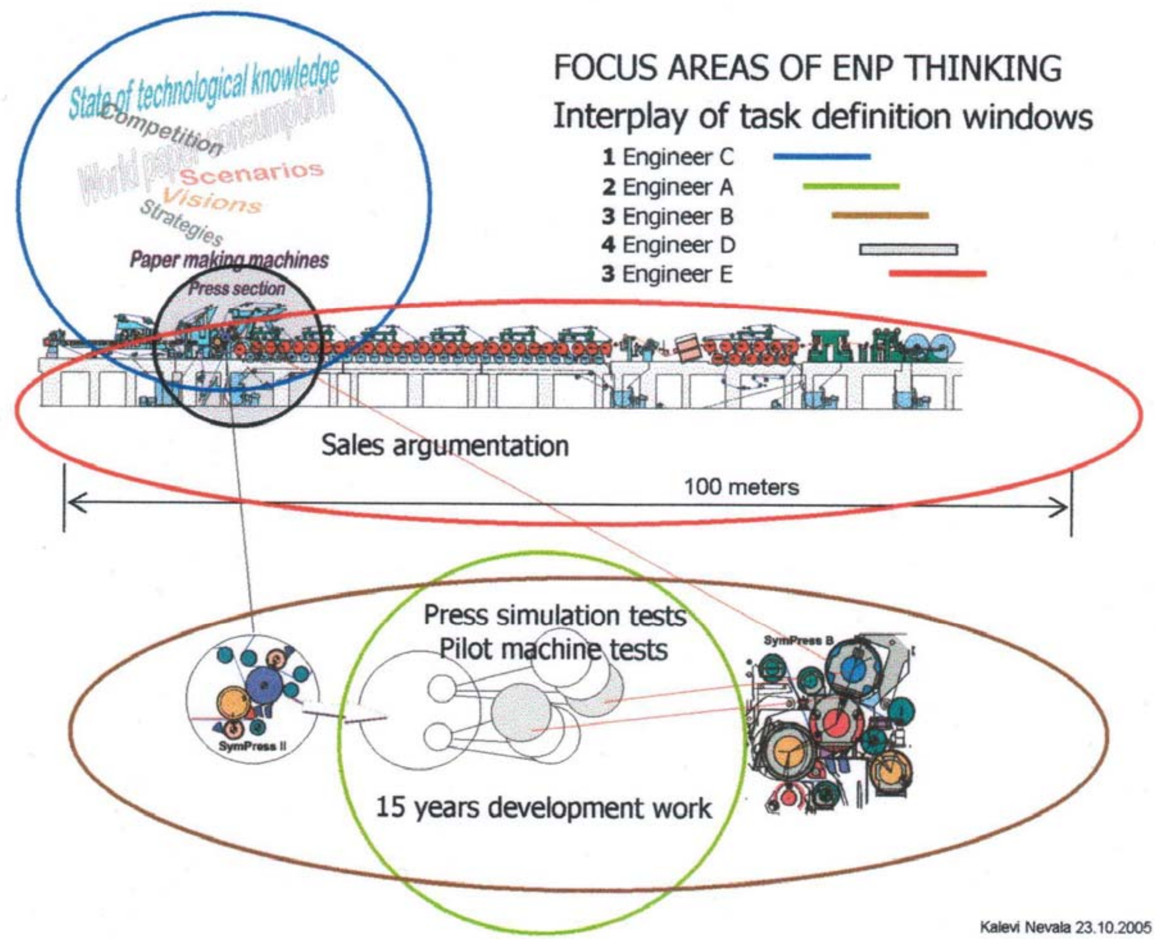


FIGURE 16 Interplay between the task definition windows of individual engineers according to the interviews (cf. Paper 4 of this dissertation).

7 SUMMARY OF DISSERTATION PAPERS

7.1 Paper 1: Constructive engineering thinking: embodying social desires

This paper is an introductory discussion about our empirical case. The main purpose was to discuss the human role in engineering design using the ENP development as an example.

The special perspective of this paper was to look at the broad context and the ultimate needs of an innovation, and show how the social overall social environment and the tiniest technical details are entangled together.

7.2 Paper 2: Content based design engineering thought research at Oulu University

In this paper our current content-based approach to engineering design is proportioned to the historical development of the human centered design engineering approach at Oulu University since the beginning of 1970s.

An introduction to our approach and the case was brought forward for the first time on an international forum by this paper.

7.3 Paper 3: Content-based design analysis

This paper is an introduction to our content-based design analysis. It presents our approach to the long-ranging empirical case. The paper states that content-based design analysis investigates design phenomena as processing mental contents and explains the phenomena on the grounds of involved mental contents. We show why and how the content-based design analysis is applicable in studying the core phenomena of engineering design, namely the thought processes of individual engineers. Additionally we discuss the nature of thinking and creativity in a large scale industrial design process. On the basis of our findings we suggest an idea of convergent creativity.

7.4 Paper 4: Mechanical engineering way of thinking in a large organization

The aim of this paper is to discuss how the expertise in developing mechanically functioning products is distributed throughout the organization. On the basis of empirical material it is shown how engineers in different organizational positions think in integrating an innovation into a working whole. A new concept of a "task definition window" is presented and the interplay between individual task definition windows is demonstrated.

7.5 Paper 5: The modes of design engineering thinking

The problem discussed in this paper is that thinking is not a unitary process. In design engineering thinking the mental representations of designed objects and the state of the plan evolve continuously during the design process. The information contents of the representations changes constantly. We need new knowledge about the movements of designers' thought processes.

Traditional psychological models, which are applied also by the design engineering traditions, divide thinking in stages or phases which follow each other in a chronological order. We suggest in this paper that thinking should rather be divided into different modes, which are not necessarily sequential.

Research on the modes of engineering thinking is a typical problem, in which we content-based analysis can be helpful.

7.6 Authors contribution to these papers

Papers 1 and 4 were written by the author alone. Paper 2 is discusses the historical background of the human centered design engineering education at Oulu University, in which the author has influenced since the beginning of 1970s. Secondly in this paper is discussed the new approach to design engineering thinking, which the author has been developing in collaboration with professor Saariluoma for nearly three years. Thereby the author has a major contribution to this paper.

In papers 3 and 5 the first author is Professor Pertti Saariluoma because the content-based thought research has been developed by him; first in the context of chess thinking, later in architecture and also in other context of economical activities. My contribution has been to bring to this collaboration the actual content elements of mechanical engineering design; paper machine design especially. The third author has provided the opportunity to obtain the empirical material and provided the expertise. I personally have done most part of the work in gathering and analyzing the document material and interviews. Additionally I have brought the necessary substance knowledge of engineering to the content-based interview sessions and over three decades long experience to the collaboration in producing these papers.

8 GENERAL CONCLUSIONS

This investigation has spotted as the main problems of design engineering processes the excessive diversity of the content elements of it, and the inadequate understanding of human role in coping with them.

In traditional approaches to design engineering processes the role of human designer has been put aside mainly due to the difficulties of investigating mental phenomena. This dissertation brings forward a new approach in investigating the human role in real-life industrial scale design engineering processes.

Content elements of engineering thinking have been self-evident to engineers throughout the times. Engineers work with them. The problems aroused only when the need for abstracting the descriptions of design engineering procedures was identified in the 1950s. When abstracting things or thoughts the true content elements fade away. They are replaced by schemes.

This dissertation suggests that content-based approach to the activities of industrial product development can provide a scientifically justified and in practice capable approach to the research on design engineering phenomena. The gap between high level abstractions of design engineering procedures and real-life thinking can perhaps be filled by a bottom-top approach through research directed to the real contents of thinking.

A four mode model of thinking was identified by our empirical analysis. The findings suggest that human thinking proceeds from a self-consistent apperceptive mental representation through a rather automatic restructuring process to a reflection and finally to constructing an integrated mental representation. Restructuring means automatic decoding of inconsistencies of the apperception. Reflection entails coping with these inconsistencies. Constructive mode of thinking has a dual function. It integrates the content elements of an individual mind to a new consistent mental representation. It also integrates all relevant organizational knowledge into the representation. Finally, the interplay between thousands of minds provides the final construction of an industrial product.

Design engineering in industrial scale is always a long-lasting process. This means that for example "think-aloud" protocol analysis, which was validated as a scientific method by Ericson & Simon (1980) and used rather widely also in design engineering research (cf. Cross et al. 1996), can not be used. Therefore, this dissertation presents a reconstructive method of coping with long-term design engineering thinking. It entails three stages: reconstructing the real changes in machines, reconstructing the progression of the plans and interviewing the participants. Integration of these three levels of information comprises our data for explaining and interpreting design engineering thinking.

This data could of course be analyzed by quantitative means which is the prevailing scientific inclination, but in such a process the true meaning of the content elements would be lost. In order to explain what has been thought, qualitative analysis of the data is necessary; but what kind of analysis? This dissertation gives one answer. This dissertation also confirms that qualitative methods in analyzing this kind of data must be developed further to meet the scientific criteria properly. This is a very important issue for future research. This investigation is only a start for a scientific approach to the content-based analysis of design engineering procedures. Much has to be done during coming years.

Content-based analysis uses objective methodology. Instead of relying totally on introspective or biographical experiences it concentrates on objective, third person perspective to human designers thought processes and the output material of them. This follows the principles of modern psychology (see Watson 1919). From the third person perspective it is possible to find information about the hidden, tacit and unnoticed aspects of the processes which do not easily open to an introspective observer.

Our reconstructive method is based on interviews, but it is from the introspective approaches, because the actual data is documented and it is thus public. It can be used by any member of design research community. Because interviews are based often on documents and statements given by other persons, the questions give more objective grounds for making inferences about the involved design engineering thinking processes.

Content-based analysis differs also from creativity-oriented ways of investigating design thinking. These approaches are based on the idea that human creativity is divergent and people need to find remote associations to be creative. In the very end, the basis of these approaches is very intuitive. By means of empirical content-based analysis a very different conception of creativity has been found (article 3). Analysis of the protocols has shown that design engineers' creative thinking is not free floating flow of ideas, but is based on very concentrated and focused thought processes. They state very clear problems, which have strong design rationale. They do not associate freely but they think how to raise the speed, how to increase the length of impulse, how to find belt materials which do not break. This new vision to creativity has been called here convergent. It is one example of the s which objectivity of content-based approach can open for the investigation in design engineering thinking.

Content based analysis differs also from information processing approaches. The most successful approach in this field has presumably been capacity oriented analysis of human thinking (see e.g. Kavakli and Gero 2003). This approach is based on the idea that human information processing capacity is limited. We can attend one thing at the time and keep in mind only a few independent units (Broadbent 1958, Cowan 2001, Miller 1956). If the capacity is exceeded, something is easily lost and outcome is a failure.

The problem with capacity-oriented work is in the notion of capacity. One can fill the limited capacity stores with any information content. Working memory does not make any difference between designing paper machine of aircraft, if only the capacity has not been surpassed. This means that it cannot explain much about the contents of designers' thoughts. Consequently, content-based design analysis opens a possibility to answer many types of problems, which cannot be asked in capacity-based analysis. Nevertheless, the two approaches are not contradictory but complementary. They can give information about different dimensions of this very complicated process.

The most important result of this dissertation is to bring forward new scientific methods for the research on design engineering thinking from a new perspective; a content-based reconstructive approach in coping with design engineering phenomena in industrial context on individual and organizational levels. This line of research will ultimately enhance the practical activities of engineering design. By understanding properly the actions of engineering thinking the administration of these processes will be easier.

The results of this inquiry suggest also that the education of engineers should be reconsidered. Engineering thinking should be emphasized in teaching of new engineers. Multi-scientific collaboration in education and research is therefore a necessity. I suggest that all parties, which are committed in advancing design engineering activities, will join their resources in educating thinking engineers.

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FINNISH SUMMARY

Tämän tutkimuksen pääteema oli etsiä uutta lähestymistapaa todellisten suunnitteluprosessien ymmärtämiseen. Tässä esitetty lähestymistapa perustuu siihen ilmeiseen tosiasiaan, että yksityisten insinöörien ajatteluprosessit ovat ainoa suunnitteluprosesseja ylläpitävä voima. Ihmisen ajattelun tutkimuksen vaikeus on suurin hankaluus todellisen suunnitteluprosessin ymmärtämisessä. Tärkein teesi tässä tutkimuksessa on, että uudella sisältöperusteisella lähestymistavalla on mahdollista ymmärtää paremmin suunnitteluajattelua ja täyttää käytännössä havaittu kuilu perinteisten suunnittelumenetelmien ja todellisen insinöörien ajattelun välillä. Perinteiset menetelmät ovat pääosin intuitiivisesti rakennettuja tai ne pyrkivät selittämään suunnittelun kulkua abstraktioista lähtien. Uudella lähestymistavalla olisi mahdollista edistää suunnittelun tutkimusta ja käytäntöä merkittävästi. Ehdotus uudesta lähestymistavasta pohjautuu laajaan empiiriseen tutkimukseen, joka tehtiin merkittävän teollisen innovaatioprosessin etenemisestä: Valmet/Metso SymBelt-puristinkonseptin kehittämisestä vuodesta 1983 lähtien. Todelliset teolliset innovaatiot ovat pitkäjänteisiä prosesseja. Ne saattavat kestää jopa vuosikymmeniä huolimatta siitä, että taloudellisista ja kilpailullisista syistä teollisuuden innovaatiosyklejä halutaan jatkuvasti lyhentää. Pitkän suunnitteluprosessin tutkiminen on mahdollista ainoastaan rekonstruktiivisella menetelmällä. On-line tarkkailu on mahdotonta ja laboratoriomittakaavan tutkimukset eivät kerro paljoakaan pitkän aikavälin ajattelusta. Tässä tutkimuksessa esitetty rekonstruktiivinen lähestymistapa sisältää kolme tasoa: todelliset koneissa tapahtuneet muutokset, suunnitelmien eteneminen ja osallistuneiden insinöörien haastattelulausunnot. Näiden kolmen tason kokonaisuus muodostaa sen tieteellisen aineiston jonka pohjalta todellista suunnitteluajattelua voidaan selittää ja tulkita. Tässä tutkimuksessa on esitetty joitakin esimerkkejä tästä aineistosta ja sen tulkinnoista. Yksi esimerkki tulkinnoista on neljän ajattelumoodin malli: ajattelu käynnistyy ristiriidattomaksi koetun apperseptiivisen mentaalisen representaation omaksumisella ja jatkuu lähes automaattisella restrukturointi-vaiheella, jossa identifioidaan muistissa olevan kokemustiedon pohjalta representaatioon sisältyvät mahdolliset ristiriitaisuudet. Kolmas vaihe on reflektio, jossa etsitään uusia ratkaisuja tunnistettujen ristiriitaisuuksien korjaamiseksi. Lopulta ajattelun konstruktiivinen moodi integroi ajattelun sisältöelementit uudeksi ristiriidattomaksi mentaaliseksi representaatioksi. Ratkaisu on syntynyt. Ajattelun moodit eivät välttämättä tapahdu kronologisessa järjestyksessä, vaan voivat olla päällekkäisiä tai sisäkkäisiä. Tutkimuksessa on myös tarkasteltu sisältöperusteisen lähestymistavan edellytyksiä edistää luovuuden ja suunnitteluajattelun organisatoristen ulottuvuuksien tutkimusta. Tämä tutkimus luo pohjaa sisältöperusteiselle suunnittelututkimukselle.