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MECHANICAL ENGINEERING WAY OF THINKING IN A LARGE ORGANIZATION

A Case Study in Paper Machine Industry

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1. Introduction

This paper is one part of a search into the **core phenomena of mechanical engineering** design, namely, the **thinking processes** of the engineers who make plans for implementing mechanically functioning artifacts; or as it is in most cases technological improvements for them. These processes comprise a wide range of engineering deliberation, from the levels of business strategy planning through the detailed design of the required equipment and components eventually to the aspects of marketing, production, delivery, operation, maintenance, repair, renovation and even disposal of the machines. I will call this ensemble of thought processes **mechanical engineering way of thinking,** irrespective of the organizational position or education of the thinker.

Research on thinking is difficult. Objective data is hard to acquire. We cannot even trace our own thought processes reliably due to the subconscious and unconscious elements of thinking. That is why psychologists have denied the scientific status of introspection for about hundred years [see for example Boring 1929/1957, pp. 641-653]. On the other hand, investigating the thought processes of another person necessitates always indirect inferences. Behaviorists rejected totally the importance of mental processes. According to them only measurable stimuli and observable behavior can be used as scientific data. By the rise of cognitive psychology and cognitive science since 1950's [see for example Bechtel & Graham 1998] the significance of mental processes has been somewhat rehabilitated. Methods like computational simulation of mental processes [Jordan & Russel 2001] and think-aloud protocol analysis [e.g. Cross et al. 1996] have been invented, but the main problem of incomplete data still remains.

Mechanical engineering knowledge is an indispensable but quite commonly undervalued resource in modern technology. In public discussion about current economy slogans like ICT, customer oriented business thinking and quarterly bookkeeping are on the surface. However, every single physical realization of the functions intended to improve customers' welfare needs mechanical engineering way of thinking. Someone must know how to build the machines; how to shape and finish the materials of the required components, how to assemble them into a working whole. On the other hand, words like **mechanical** or **machine**, and even the core subject areas of mechanical engineering education, lead us easily to conceive the competence area of the discipline too narrowly; merely as an expertise in dimensioning, tolerances, fabrication techniques, and alike. However, in a real world design – in industry or at backyard – the mechanical engineering *designer* must administer explicitly or tacitly all attributes and factors, which determine the **functionality, feasibility** and **consistency** of the product. In other words, the competence requirements for a mechanical engineering designer comprise the capability to bind together a vast amount of multi-disciplinary knowledge. **How is this performed? What do the mechanical engineering thinkers actually do?**

There is a strong tradition in the research on mechanical engineering design [e.g. Hubka & Eder 1988, Pahl & Beitz 2003, VDI 2221, VDI 2222, VDI 2225, Ulrich & Eppinger 2000, Ulman 2003], which has explained very successfully the procedures. During the last decade very interesting approaches to these questions have been made for example in Germany, e.g. between Darmstadt, Munich, Berlin and Bamberg Universities.

2. Theory and method

I have approached above questions empirically through collaboration between the Laboratory of Machine Design, Oulu University, Cognitive Science, Jyväskylä University, and Metso Paper Inc., Jyväskylä. The empirical study was carried through in 2003 – 2005 at Metso Paper Inc. Rautpohja Works, in Jyväskylä Finland.

We call our approach **content-based design analysis** [Saariluoma et al. 2005a]. It is based on the basic principles of content-based psychology [Saariluoma 1995]. In content-based analysis we explain the phenomena of engineering design on the basis of **mental contents of the assigned engineers**.

In order to reveal the mental content we have chosen **reconstructive** approach. This is necessary because we want to investigate engineering thinking in a real life industrial context, where innovation processes can take even decades. Therefore, on-line monitoring is impossible. Reconstruction entails interviews and document analysis. We performed it on three levels: (1) **hardware level**; we traced the real changes in machines and processes, (2) **plan level**; we reconstructed the overall proceeding of the innovation process, and (3) **thought level**; we made inferences about what really happens during the processes of generating and transforming the mental representations of participating engineers.

The main tool of our method is explaining the interview statements through the interaction between these three levels: some inconsistency triggers the need for improving the hardware. This generates mental representations in the minds of the assigned engineers. The **thinking-action cycles** of the engineers produce propositions, sketches, drawings and specifications, that is to say, plans which will consequently change the mental representations and eventually the hardware. Our focus is on the **content-based logic of the mental representations** of individual engineers. By investigating this we hope to reveal means for improving the innovation abilities of engineering organizations. We aim to develop the content-based reconstructive design analysis to the level of a standard method in design engineering research.

We have spotted many interesting features of design engineering thinking [e.g. Saariluoma et al. 2005a, b, Nevala in press]. In this paper I will concentrate on a couple of aspects. First, I will sketch an overall picture of how the investigated innovation process was comprehended by the five interviewed engineers through their individual "**task definition windows**" and secondly I will discuss briefly how these "comprehension spaces" have interacted during the process. More comprehensive discussion will be provided later [Nevala in press].

3. The case

The empirical case of our investigation is the development of so called extended nip press (ENP) for paper machines 1983 – 2003 (Fig 1).

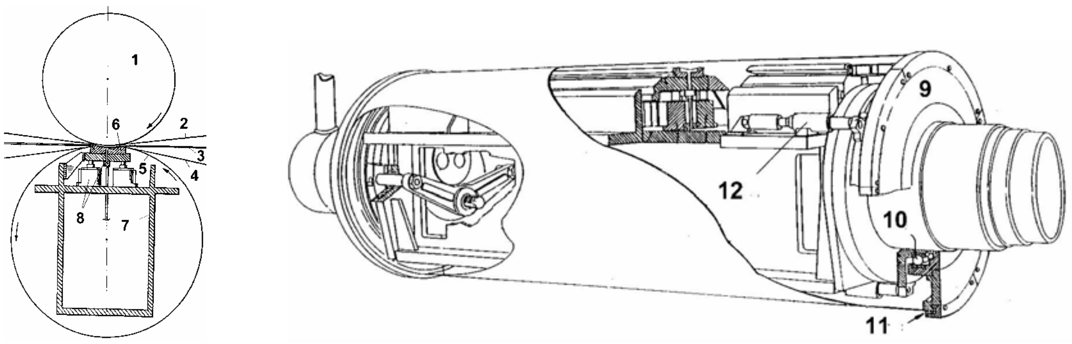

Figure 1. . Schematic illustration of an assemblage of ENP roll for paper machines (adapted from patent publications, Finland 2000 and PCT 1993b)

ENP provides a wider contact zone (i.e. the 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. The flexible roll is driven by the upper roll through friction forces. This innovation has been a major breakthrough in papermaking technology. It enables considerable increase of production speed in economical terms or alternatively equivalent savings in the energy costs.

The idea of an extended press zone in the dewatering presses of board and paper making machines is old [see for example patent publications; Canada 1948; USA 1966; Germany 1972; USA 1974; Canada 1975]. 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 1970’s the technology was lacking – or was believed to be lacking – for 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 considered to require uneconomically robust structures. But 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 lacking until late 1970’s. An additional reason for the mild interest in advancing this innovation was the excessive “patent jungle”; for example the German Escher Wyss GmbH had in the beginning of 1980’s alone over 700 patents concerning ENP, and the East German originated patent from 1972 was judged by the experts of Valmet restricting the commercial use of the concept so severely that all efforts were suspended.

The culmination point of the history of ENP was the delivery of the first production scale open belt “shoe press” (Fig. 2) for a board making machine in Springfield, USA 1981 by Beloit Corporation (USA).

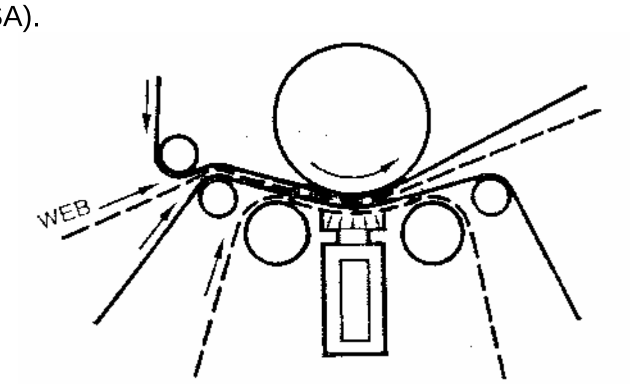

Figure 2. The principle of an open belt extended nip press ENP (Justus and Cronin 1982)

This breakthrough was a joint venture of Beloit and the belt producer Albany, and it alerted other paper and board machine producers. This is the starting point of our inquiry. We have reconstructed the process of coping with this challenge at Valmet / Metso Paper Inc. We have had a unique possibility of interviewing five engineers, who were centrally engaged in the development process. All five engineers have been looking at the same product development process for many years from their own angle and scope of view. One from the point of view of the project manager of the target project from the beginning; one from the company's product development department; one through paper machine tender planning activities; one from the perspective of the corporate level product planning; and one from paper machine sales department. All of them are – one way or another – connected with mechanical engineering, but have been working in diverse organizational positions and assignments. The obtained material includes over 17 hours of individual and group interviews, wide assortment of organizational documentation and about hundred patent publications. Figure 3 illustrates the overall schedule of the target innovation and the periods, when interviewed engineers participated in the process.

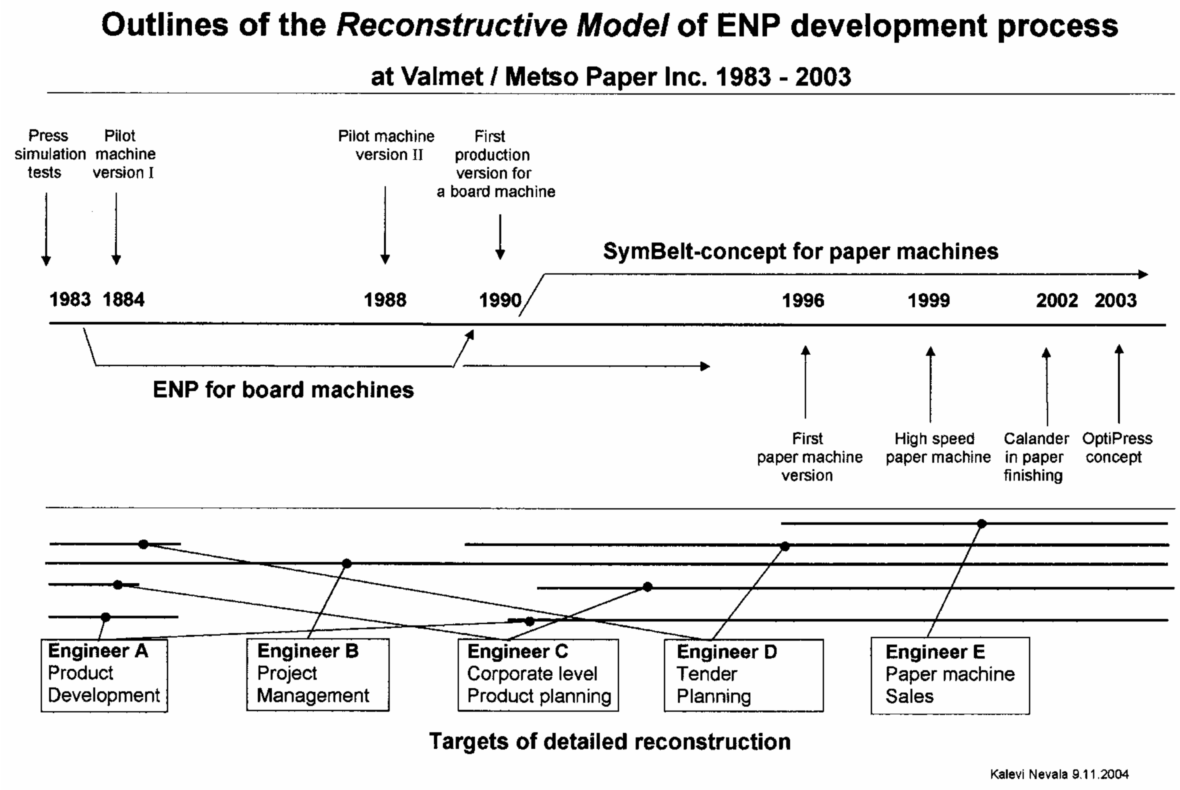

Figure 3. Periods of participation of the interviewed engineers.

4. Empirical results

One of the foremost features of engineering thinking, which the empirical material indicates, is that an individual engineer comprehends the total papermaking scenery through a restricted "window". The boundaries, or frames, of the window are determined by the personal knowledge and by the organizational position of the individual engineer. The task setting is consequently guided by these boundaries.

Another major finding is that the contents of design thinking are very strongly socially, even globally shared. The realities of the papermaking science and industry dictate the rules and boundaries of paper machine design. Nearly all fresh product development engineers propose radical improvements in papermaking. But when they get themselves acquainted with the three basic requisites of papermaking the alternatives diminish.

Furthermore our empirical material reveals a logical dynamic cycle between long-lasting thinking processes of the five key engineers during the innovation process.

The overall cycle consists of **corporate level** view on business development (CASE 1 bellow), which led to **test programs and pilot** projects (CASE 2), which led to detailed **product development** (CASE 3), which led to adapting the new component in **tender planning** (CASE 4), which led to utilizing the new innovation as an attractive sales feature by the in **paper machine sales** (CASE 5). Eventually this cycle improved the corporate level business of Metso Paper Inc. by providing customers new means for considerable increase of production speed. The innovation cycle was completed. It took almost 15 years before this 1983 started innovation was in full use in paper machines. About seven years long sub cycles were detected; (1) ENP for board machines 1983 –1990, (2) SymBelt Press for paper machines 1989 – 1996 and eventually (3) applying SymBelt Press in OptiPress by 2003 (see Fig. 3)

Five different mental views and task definition windows were incorporated. They interacted by the functional rules of the organization, global markets and technological facts.

As Fig. 3 illustrates, the thinking processes must have been very elaborate. Indeed, our empirical material includes a versatile assortment of data which can be used for elaborating the picture about the scope and contents of the thinking processes. In this paper it is possible to cover only a small fraction of the total complexity. The purpose of following cases is therefore to provide only an overview by few brief examples.

4.1 Outlines of five task definition windows

CASE 1

Question: How is your education as a mechanical engineering designer connected to your current professional identity?

(T10: 00,00,48)[1]: *… 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 for advancing 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 meta-level.*

(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…*

Explanation: This statement clarifies an example how mechanical engineering thinking is connected with the business level strategic thinking. An educated mechanical engineering designer acquired totally new thought processes, when assigned on the level of the total business activities. "Looking at the starting phase of technologies" seems to mean wider perspective. Machinery is not the most important, but always necessary. The main tools of this engineer were scenarios of future paper consumption in the world; complemented with professional abilities to understand what kind of products paper machine industry would need to cope with the changes.

Conclusions: These quotations reveal the frames and contents of the task definition window of this particular engineer, i.e. the building materials of the active mental representation of

[1] Position on the interview recording CD: Track 10; (00 hours; 00 minutes; 48 seconds)

the assignment. Further investigation showed that this globally wide task definition served as the basis and starting point for several strategic decisions in Valmet paper machine development work: e.g. Press-83 project, which led eventually to the ENP project (our case) and decision in 1989 to double the production speed of paper machines, which ultimately justified the ENP for fast paper machines. These strategic decisions in turn defined the frames of the task setting in the other cases presented below.

CASE 2

Question: What are the roles of product development, paper machine design and external design services?

(T7: 00,08,02): *… External services deals with the design department… Design department has little capacity, so they buy from outside… Product development doesn't use outside services, we design components for pilot machine and we have our own designers…*

…the pilot version of ENP was designed by our designers… we [the product development engineers] provided them the facts about the Beloit-concept.

Explanation:

Conclusions: Due to his organizational duties this engineer focused his task definition window to press simulation tests and test runs with the pilot paper machine. Therefore he was natural choice to participate in projects which were intended to asses the feasibility of ENP.

CASE 3

Question: Could we look at the changes in ENP?

(T16: 00,01,00): *… If we start from the beginning, we knew the Beloit open belt concept and the patents of it… Also Voith had recently introduced closed concept… Our purpose was to make an invention which can be patented and is better than competitors' equipment… Beloit had patented a simple hydrodynamic bearing… or actually the joint… We thought that we can use two cylinder to accomplish a virtual joint…*

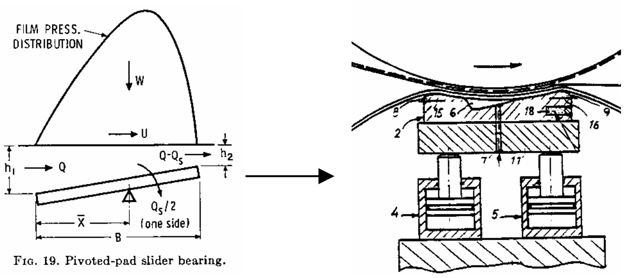

Figure 4. Replacing simple mechanical joint by a virtual joint by two cylinders

Explanation: This engineer was responsible 1986-1990 for developing a SymBelt Press for Valmet board machines (Fig. 3). Above quotation reveals a very important factor influencing the thinking of engineers: development was triggered by competitors' patents. Valmet's strategy was to be the best second at the markets. The engineer also attended the above mentioned test programs and pilot tests assessing the feasibility of ENP. His work culminated to the design of the press nip (Fig. 5), even though he was responsible of whole construction (Fig. 1).

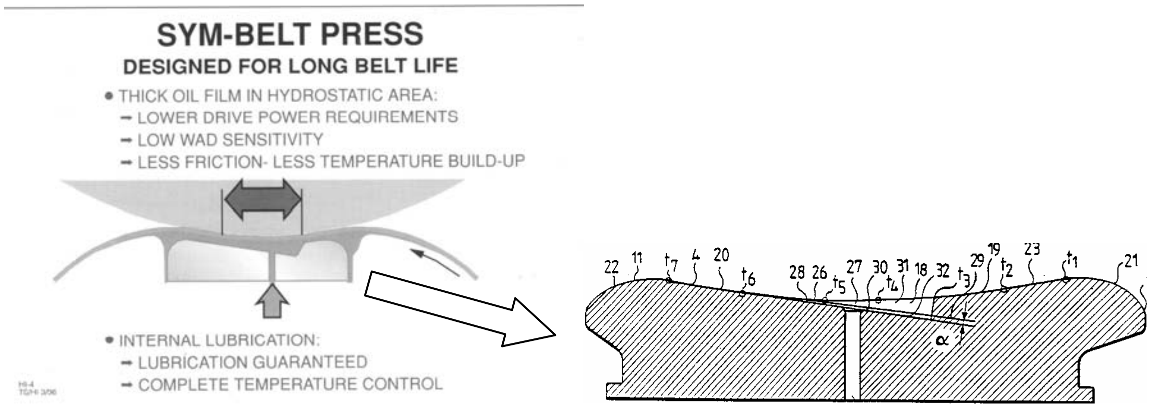

Figure 5. Principle of Valmet / Metso SymBelt Press and details of press shoe

Conclusions: The task definition window of this engineer was focused (1) on the preliminary tests, (2) on the detailed construction of the press (Fig. 1) and the process in the press nip, (3) on the productisation of ENP. The details and scope of his task definition window is most extensive and versatile among the interviewed engineers.

CASE 4

(T5: 00,02,15): *… We get from our board machine factory (in Sweden) the actual workshop drawings, then we can adjust the eventual positions, alignments and tilts [for a particular tender drawing]… They also manufacture the belt roll for all SymBelt Presses in Sweden…*

(T5: 00,32,45): *… As I have done these [tender plans; in this example a renovation of press section] ten years, one begins to see what should be done… For example here we had to arrange more room for the belt roll. The frame had to be rebuilt [see fig. 4]. Here you see, the belt roll wouldn't fit. The beam here would have to be cut off… So we made new frames. Additionally we could put here a larger suction roll.*

… It is like chess playing with these components.

Explanation: Today the belt roll is an industrial quality product. It is produced by one factory of Metso Paper and applied to paper machines by another. This engineer utilizes the belt roll as one component in the total arrangement of press section of paper machines. Major part of ENPs have been built to old machines. So called SymPress II is changed to SymPress B concept (fig. 6).

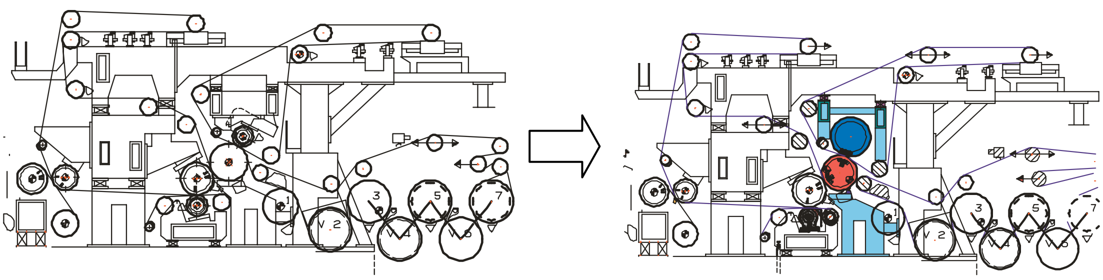

Figure 6. SymPress II (1983) and SymPress B (2003) in same paper machine.

Conclusions: In this example the twenty-year long development process is crystallized. The tender planning engineer gets on his table the drawings of the old machine and starts playing "chess" (or maybe more aptly "puzzle") with the components in order to get them into right positions. This engineer seems to be an experienced player. His task definition window is focused on whole press section on the component level.

CASE 5

Question: How is mechanical engineering connected to your current professional identity?

(T1: 00,00,25): *… Actually it is rather loose… this connection between mechanical engineering and my present profession… I consider myself as a business person, salesman… And then if something about technical matters… so I think more from the customers' point of view… Actually I have half purposely opt out of machine technical matters.*

(T1: 00,14,13): … *I use lot of technical argumentation, but which of them are mechanical engineering… I use frequently argumentation about what the machine can do… Sometimes when talking for example about profiles [of paper web], I can deepen a bit and tell how we do it, and why it is better for the quality of paper…*

Question: What was your first contact to ENP?

(T1: 00,14,45): … *Sometimes in 1980s… We followed up when our competitors introduced it for thick board grades. There was a general opinion that it wouldn't work in thin paper grades… They need high nip pressure; thick grades need a longer pressing time. But, then in 1990s the thinking was changed and I became involved… I am not sure was it so that competitors forced us, or was it our own decision…?*

Explanation: This engineer came involved with ENP project only in mid 1990s and is apparently therefore just faintly acquainted with the earlier phases of the project. Even today ENP is minor concern for him.

Conclusions: Obviously, despite intentional receding from technical matters this sales executive still employs mechanical engineering way of thinking. The task definition window is focused on paper producers business, but mechanical engineering way of understanding functional and operating matters seems to be still efficient.

4.2 General aspects of paper machine design thinking

Previous cases give only a glimpse of the factors which determine the frames and contents of the task definition windows of engineers. Following summary is based on the analysis of interview statements and documents. It is not comprehensive. More details will be discussed later (Nevala in press).

1. THINKING IS BASED ON GLOBALLY SHARED PAPERMAKING TECHNOLOGY
   - Experienced engineers have an established working space, where the boundaries of possible and necessary solutions, as well as norms have been building up years
   - Probably every engineer has been thinking through radical changes to paper machine, but basic principles have survived for generations
   - Same logically good propositions recur generation after generation; but they don't work in practice

Conclusions: Knowledge contents of papermaking is so manifold and fine grained, and is composed of so diverse knowledge types that explicit administering of all attributes and effects of new proposals is not possible. This emphasizes the importance of company cultures as the mediator of unspoken knowledge.

2. QUALITATIVE EXPERIMENTIAL KNOWLEDGE IS IMPORTANT
   Acquiring a "touch" is based on:
   - Knowledge about running production machines
   - Personal touch in testing equipment and processes
   - Runs of pilot paper machine

- Personal understanding of physical and machine technical phenomena
- Analogies

3. FUNCTIONAL RULES
There are three “umbrella” rules, which must always be fulfilled simultaneously in order to get a functioning solution:
- Paper technical grade-specific requirements must be fulfilled. That is, the properties (e.g. fiber structure and surface qualities) of the produced paper must be right,
- Runnability of the whole paper machine line must be maximal.
- The solution must be machine technically feasible and functioning.

These rules compile and crystallize a large range of necessary functional rules and constraints of the diverse knowledge involved in papermaking.

5. Discussion

The purpose of this paper has been to give some idea of the thought processes of engineers and the interaction between them. The focus here has been on the factors which cause natural constraints to thinking in paper machine design. These constraints explain, in their part, the economy of thinking of experienced engineers: they know where to concentrate.
A new concept of task definition widow is introduced and some examples of the frames and content of it is provided. This concept is a tool which hopefully helps analysing human thinking by content-based criteria. It also helps in understanding the interaction of several engineers within organization. Furthermore, this approach helps to understand better the premises of creativity; totally free floating creativity seems to be only a minor tool in productive creativity.
This paper is one part of larger research effort, which we call “content-based design analysis”. Other features as the modes of thinking has already been introduced in content-based terms [Saariluoma et al. 2005a,b, Nevala in press].

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