NordDesign 2004 – Product Design in Changing Environment
18-20 August 2004, Tampere, Finland

WEIGHT REDUCTION OF SUPPORT STRUCTURES

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Keywords: FEA, Optimization, Metal Structuresc

Abstract

In modern engineering industry the weight reduction of support structures of machines is important. One possibility to reduce the weight of the support structures is to use sandwich configuration. Mechanical properties of sandwich structures are characterized by higher strength-to-weight and stiffness-to-weight ratios than those of stiffened steel plate structures.
In conceptual phase topological optimization has been performed, that allowed to find structurally sound initial model for further design and parametrical optimization. Topological and parametrical optimization has been performed using commercial finite element analysis software system. Using parametrical 3D modelling and finite element analysis allows considerable flexibility of designing products with different configurations, which is very important in shortening time to market with new products.
In the current study, welded steel structures consisting of walls and ribs welded in between them are proposed. The strength properties depending on ribs configuration and the length of welds have been examined. Manufacturing of such structures requires new technological approach. Some technological adaptations for construction of sandwich frames are also described in this paper. As an example, the design and reduction of mass of brush-cutting machine's body has been investigated.

1 Introduction

An important problem in industry is how to achieve better design concepts by considering product performance and manufacturing costs in the early design stages of product development. It must be possible to manufacture the final optimal product economically, and the product should consist of standard and simple geometric shapes instead of arbitrary complex shapes.
The topology of a product has a significant effect on product performance and manufacturing costs. The initial design concept may lead to inefficient structural design and manufacturing

costs if the topology is not optimal. The design of optimal topology allows design goals to be reached faster, accurately, and cost effectively. It provides an initial design concept for subsequent applications following the design stage, such as shape optimization, machining, etc. Therefore, it is important to choose the optimal structural layout during the early design stages of product development.

The support structures of many machines are designed as frames or plates. Often they are made of steel plates that have been strengthened with various elements (pipes, angles etc.). As an example we studied a brush-cutting machine's body (Fig. 1). The mass of such a structure can be reduced by using a sandwich structure.

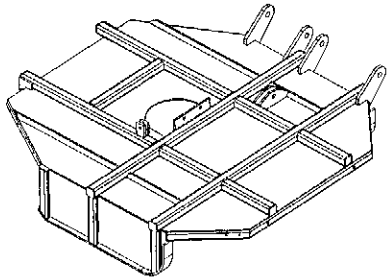

Figure 1. Brush-cutting machine's body before optimization

One possibility to build sandwich structures is to place ribs between the two covering layers. Forces influencing the structure in working state differ by direction, character and power. The problem is how to place the ribs so that the usage of material is optimal. A good way to solve this problem is to use topology optimization.

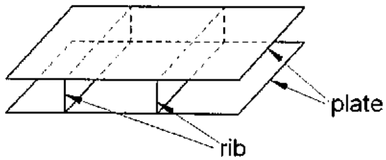

Figure 2. Sandwich structure

2 Topology optimization

Topology optimization, which was introduced by Bendsoe and Kikuchi [Bendsoe & Kikuchi, 1988], is usually used to find the optimal distribution of material in a given design region that meets a predefined criterion [Leiva et al., 1999]. With topology optimization, regions of the structure that have the least contribution to the overall stiffness or natural frequency can be identified. Thus, it enables identification of the regions, which should be taken out from the structure to minimize the mass with the least impact on the performance of a structure. Of the various optimization techniques, topology optimization has proven to be very efficient, especially when used to strengthen existing designs [Chen & Usman, 2001].

Unlike traditional optimization, topological optimization does not require the explicit definition of optimization parameters (i.e., independent variables to be optimized). In topological optimization, the material distribution function over a body serves as optimization parameter. The user needs to define the structural problem (material properties, FE model, loads, etc.) and the objective function (i.e., the function to be minimized or maximized) and

the state variables (i.e., constrained dependent variables) must be selected among a set of predefined criteria.
The theory of topological optimization seeks to minimize or maximize the objective function (f) subject to the constraints (g_j) defined. The design variables (η_i) are internal, pseudo densities that are assigned to each finite element (i) in the topological problem. The pseudo density for each element varies from 0 to 1; where $\eta_i \cong 0$ represents material to be removed; and $\eta_i \cong 1$ represents material that should be kept [Ansys, 2003].
The steps of optimization approach using topology optimization can then be stated as:

- identify the design space for the analyzed body,
- create the topology optimization model,
- formulate the optimization problem based on design requirements,
- perform topology optimization,
- create an optimized design based on the optimization results.

3 FE modelling and simulation

The selected plate has side measurements 1.4 x 1.4 m. Very typical is the bigger opening in the centre of the plate for fastening an engine or another device/structure. For this purpose an 0.3 x 0.3 m opening has been made in the centre of the plate. Usually bodies are supported from two sides plus one additional constraint, or from four corners. The most usual load cases are:
a) force is directed to the centre of the plate (e.g. Booms of a lift, Fig. 3 a, b);
b) force is directed onto one corner (when a tree or a rock is hit, Fig. 3 c);
c) torsion loading (riding on uneven landscape, Fig. 3 d);
d) force is directed to the centre of one side (Fig. 3 e);
e) moment loading on the opening in the centre of the plate (e.g. boom of a lift, Fig. 3 f, g).

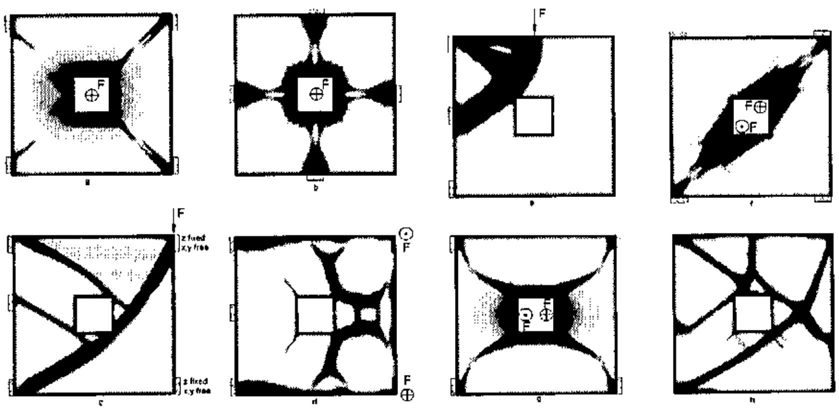

Figure 3. Square plate topology optimization results of different load cases. Darker area means greater density

A corresponding topology was found for each load case. Also the best topology of the structure was found for the combined loads. As large models may take long time to solve, it is preferred to use many several simple analyses to study the physical phenomena involved and to find out parameters (for example contact parameters, element parameters etc) in order to avoid unsuccessful simulation with large models. [Adams & Askenazi, 1999]

Topology optimization was performed with the FEA software suite Ansys 7.1. For simplifying the task the structure was modelled as a thin plate with thickness 10 mm. Shell 93 elements were used for modelling. 3D solid elements are planned to be used in future work. During optimization global structural stiffness was maximised by reducing the volume of the structure by 80%. It is not allowed to modify the material on the edge of the plate and the edge of the opening. Modifying the rest of the material is allowed. The selection criteria for the loads influencing the plate were following:

1) stress should not cause yield stress (<380MPa);
2) deformations caused by the force should remain small.

After calculation the results should be critically evaluated and the model should be updated [Friswell & Mottershead, 1996] if necessary. One possibility to verify the model is to set up a test (Computer Aided Testing) and examine how the structure behaves under the real conditions [Montgomery, 1991]. Nowadays the experimental modal analysis [Cyril et al. 1986] is widespread, especially in solving problems of structural dynamics.

In the case of only one force influencing the structure Fig.3 a-g the results correspond with expectations – the force should be directed away by the shortest possible route. In the case of simultaneous influence of different load cases Fig 3h the result is more complicated. The topology depends significantly on the proportion of single force's influence in the whole solution. In the examined case all forces were considered having equal weights. Still it can be seen that load cases Fig.3c and Fig.3e have more significant influence. The results depend greatly on the application point of the force and the location of support structures.

Calculations with exact measurements confirm the solution reached by topology optimization. The best structure for given loads has 8 ribs forming a cross and a diagonal inside the structure.

4 Design of sandwich structure

There are two possibilities to weld ribs between upper and lower plates of sandwich structure (Fig 2):

- In the first case the ribs are welded on to the lower plate and the upper plate is welded on to the existing structure afterwards (Fig 4). The upper plate has holes, through these holes the upper plate is welded on to the ribs. The assembling is quite complex in this case.

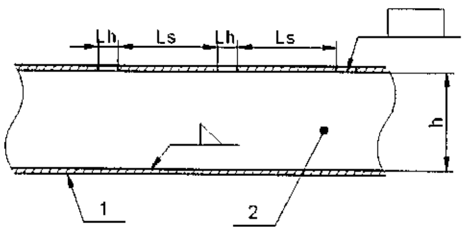

Figure 4. 1-plate; 2-rib; L_h-length of weld; L_s-step length

- In the second case the plates have slots. Slots are easy to make on the sheet metal CNC punch press. A rib plate is teethed: longitude Lh and Ls between (Fig. 5). During the assembly the ribs teeth are placed into slots of lower plate and fixed. After that the upper plate is placed and both plates are welded to the ribs.

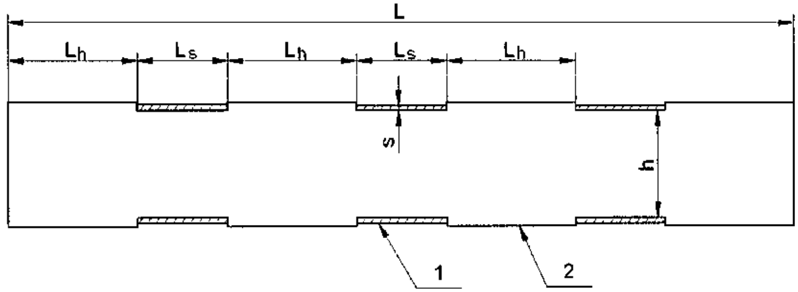

Figure 5 Toothed rib, the measurements of tooth are L_h and L_s , where 1- plate; 2 – rib;

However, welded length (teeth length) must be long enough to ensure rib stability. Modal analyse was used to study rib stiffness according to the teeth length and the teeth number. Rib stiffness was evaluated by analysing eigenfrequencies (see Fig 6). Higher first eigenfrequency was considered as greater stiffness.

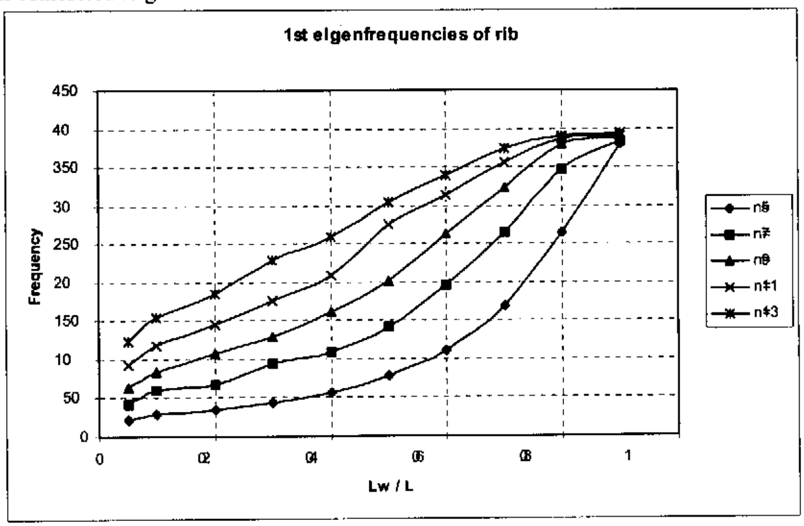

Figure 6. n - nr of teeth; Lw-weld length ($Lw=n \cdot L_h$); L_h - rib tooth length; L- rib length (Fig. 5)

Increasing the number of teeth affects to the rib stiffness more than increasing the weld length as we can see on Fig 6. Therefore it is reasonable to make lot of short welds.
Replacing stiffened plate by sandwich structure the mass of a brush cutting machine's body was reduced by 35% (Fig. 7) without essential change of strength properties, see Table 1.

Table 2. Strength properties of initial design and new design

	Initial design	New design
max. stress (MPa)	132	61
max. deformation (mm)	0.5	0.8
1^{st} eigenfrequency (Hz)	73.6	69.5

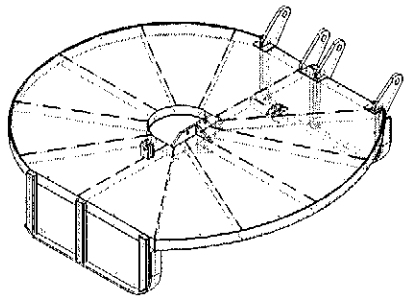

Figure 7. Brush-cutting machine's body after optimization

5 Conclusion

Increasing the number of teeth affects to the rib stiffness more than increasing the weld length, therefore it is reasonable to make lot of short welds.
Applying topology optimization algorithms enables to design sandwich structures with the better mass and stiffness rate.
The topology optimization helps to achieve better design concepts by considering product performance and manufacturing costs in the early design stages of product development.
The design of optimal topology allows design goals to be reached faster, accurately, and cost effectively.

Acknowledgements

The authors would like to thank Estonian Science Foundation for providing the research grants G5600 and G5903.

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WHEN AND HOW INNOVATION BEGINS?

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Innovation, Front End of Innovation (FEI), Opportunity Identification, Idea Generation

Abstract

Innovation and product development are conceptual relatives. Different authors have defined and described them rather divergently. The conceptual inexactness has characterized the descriptions of those processes (especially their initial activities). This paper considers uncertainty about the exact moment when the innovation process begins and what kind of activities is initiating it. The Front End of Innovation is usually called "Fuzzy Front End", because its core nature has been assumed inherently fuzzy. This assumption may be wrong because of its inadequate conceptualization and the inadequate designs of actual FEIs. We propose that the opportunity identification is logically the foundational initiation stage before the idea generation and concept definition and it is possible to design it with any fuzzyness.

1 Introduction

This paper has originated from our activities in Project RID that aims to generate corporate cultures for breakthrough innovations [Eloranta,Riitahuhta&Karvinen2002]. We have focused on issues of the front end of innovation (FEI). Therefore it is obvious why we try to be careful in respect to the true nature of FEI structures and processes. We agree with Koen and others [Koen2003, Koen et al.2001, 2002] that it is important to replace the more traditional term 'fuzzy front end' (FFE) with the term 'front end of innovation' in order to emphasize the need of conceptual clarification and demystification in respect to this initial phase of innovation process.

In a Finnish training document on innovation management, the description of innovation begins with the notion of 'idea' (Figure 1). These authors do not explicate the detailed content of idea, but they say that an idea is generated by a creative activity [Malinen&Barsk2004, p 40]. They note that in the fuzzy front end (FFE) the role of knowledge acquisition is emphasized in the sense of rapidity and analysis of the most recent knowledge about customers, markets, technology development, and competitors. Later in their text, they speak of idea portfolio as the first element in the ordered set of innovation portfolios.

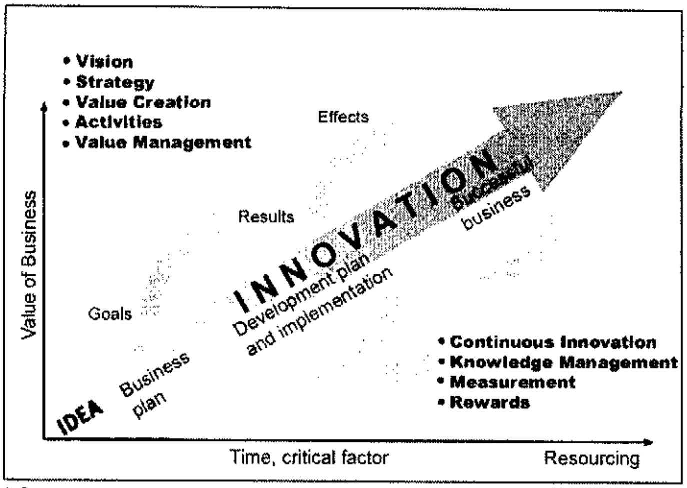

Figure 1. A framework of innovation process and innovation management [Mallnen&Barsk2004, Figure 19, translated from Finnish]

In our paper, we try to find out a more diversified view of FEI and its elements. One motivation for this quest is Koen and others' finding that the high innovative companies and the low innovative companies do not differ significantly in respect to their new product development (stage-gate) processes, but they differ significantly in respect to their FEI processes (Figure 2). This fact has been also the central motivating factor for the studies by Koen and others (more details in chapter 4 of this paper).

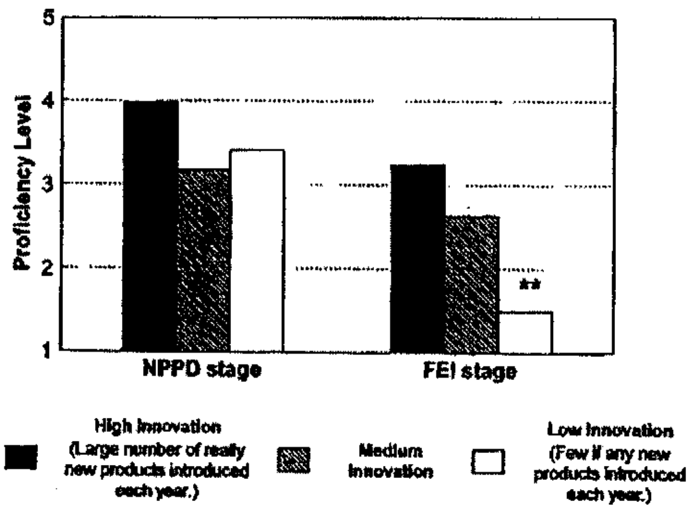

Figure 2. Proficiency differences between high, medium and low innovation companies in Front End of Innovation (FEI) and New Product/Process Development (NPPD) stages [Koen et al.2001, Figure 3]

Our paper has the following structure. The next chapter describes two textbook models of new product development and especially their contents of initial phases. Both of them contain explicit references to opportunities and their identification. The chapter three will provide you examples of the conceptual evolution of NPD models in respect to the front end phase. Especially we want to emphasize Cooper's Stage-Gate model's development in its front end. The chapter four describes two dedicated models of FEI, which give us more elaborated views about FEI elements and processes. In the end of this chapter we borrow Koen and others' figure that shows the relative importance of different FEI elements in respect to proficiencies of high vs. low innovative companies. In the concluding part, we present our tentative answer to the title question.

2 Models of product design and development

2.1 Ulrich & Eppinger's generic model of product development

The generic product development process consists of six phases (Figure 3). The planning phase is presented in more detailed in the lowest part of the figure.

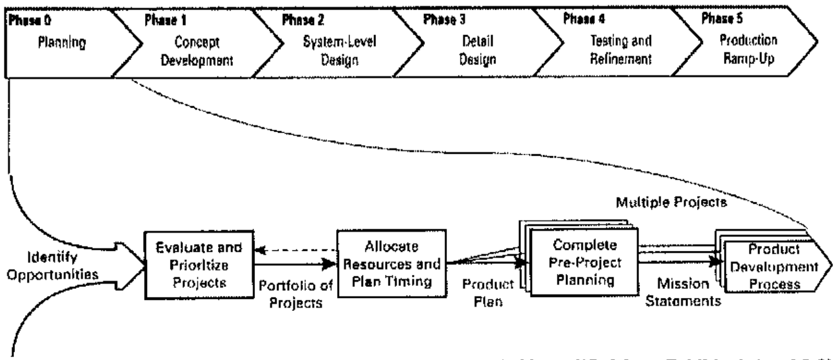

Figure 3. The product development process [Ulrich&Eppinger2003, modified from Exhibits 1-4 and 3-3]

The planning phase precedes the approval of development project. The output of this phase is the project mission statement, which specifies the target market, business goals, key assumptions and constraints. The first and important step of planning phase is identifying product opportunities. The input to the opportunity funnel can come from across the enterprise. Opportunities may be collected passively, but proactive approaches to the opportunity identification are recommended [Ulrich&Eppinger2003 p 37].

Note that this model does not contain explicit references to idea generation or concept definition like some more dedicated models of FEI.

2.2 Cagan and Vogel's iNPD model

Cagan and Vogel's product development process is presented in Figure 4. Their book concentrates mainly to the Fuzzy Front End of the product development process.

Cagan and Vogel's complete product development process contains concept generation, product refinement, production prototypes, and launch preparation phases (Figure 4). The concepts are generated during the Fuzzy Front End. The iNPD process contains four phases: Identifying, Understanding, Conceptualizing, and Realizing Opportunities. All these four phases are part of the Fuzzy Front End.

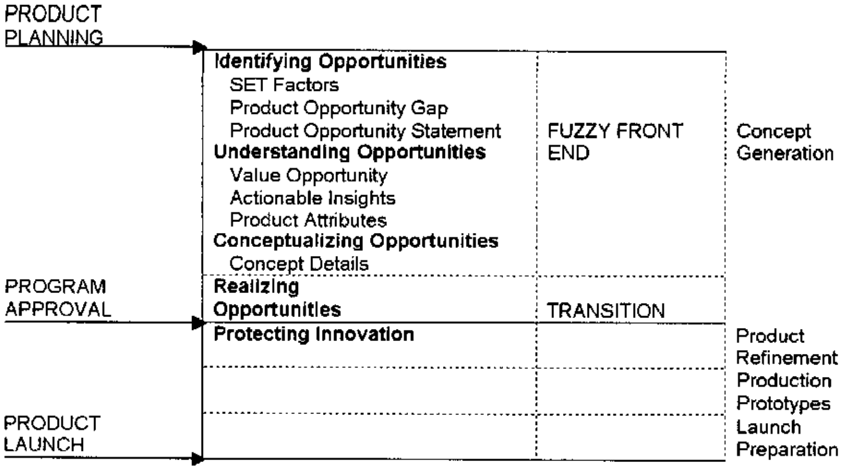

Figure 4. Product development process [Cagan&Vogel2002, modified from Figure 5.1]

The iNPD process is structured as a series of funnels [Cagan&Vogel2002, Figure 5.2]. During each phase, many alternatives are created and one is selected to move to the next phase. The model describes product planning as a set of opportunity processing activities. And they define collectively the content of concept generation.
Like Ulrich and Eppinger's model, this model does not contain an explicit reference to idea generation. Perhaps these authors consider the notions of concept generation and idea generation as synonyms. In any case, these models provide us clear evidence about the varying uses of language in the descriptions of the front end activities.

2.3 Movements toward the front end of innovation (FEI)

A kind of conceptual evolution can be found in the development of product design and development frameworks in respect to their descriptions of FEI. This evolution associates to both the general model building and to the evolution of the individual authors' models. We consider here at first Cooper's Stage-Gate model's evolution, because this model has been very paradigmatic and because many readers who have read the second edition of Cooper's book *Winning at New Products: Accelerating the Process from Idea to Launch* do not recognize the important changes in the third edition of this book. Especially this change associates to the description of Stage 0 or FEI. Our second example is Wheelwright and Clark's presentation of a set of developmental funnels. They are explicitly recommending a more emphasis on the front end of developmental funnels.

2.4 Cooper's Stage-Gate model

During the last ten years, many companies have tried to improve their product development processes according to the recommendations of Cooper's Stage-Gate model. The original model starts with a box 'Ideation' and does not contain any detailed description about its specific structures and processes. It simply assumes that adequate ideas are coming in some ways, but it does not provide any recommendations in respect to its designing.

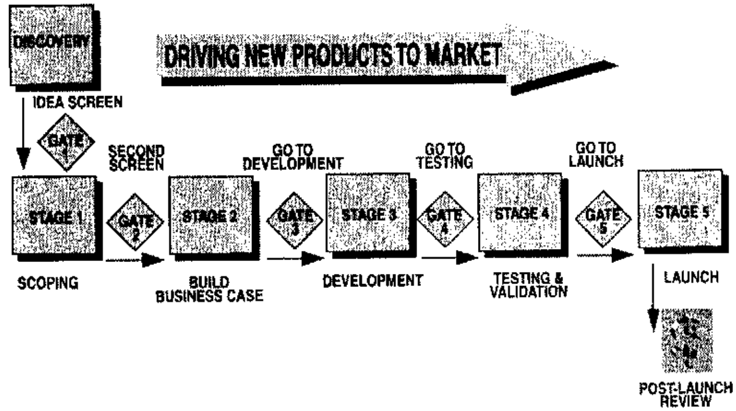

Figure 5. Cooper's Stage-Gate model [Cooper2001, figure on the front cover].

The Stage-Gate model presented in the third edition of Cooper's book starts with the box 'Discovery' (Figure 5). In this edition, the whole new Chapter 6 with the title "Discovery: The Quest for Breakthrough Ideas" is dedicated to the description of it. Also some other chapters of this book contains materials associated to FEI; for example, when Chapter 5 considers seven goals of a new product process, it presents Goal #6: Better Homework Up-Front. The Discovery chapter 6 begins with a subtitle "The discovery stage: Ideation" and an introductory sentence: "After a decade of development focused on extensions and quick hits, the quest for the super-idea – the "home run," breakthrough idea, or major innovation – is quickly becoming a key management issue." And the next paragraph explains this change of the book: "So important is idea generation that I now treat this as a separate stage. In the previous edition of this book, the idea stage was treated as a given; it was always assumed that there are lots of ideas sitting around waiting to be worked on. Perhaps this is true, but the quality of these ideas is lacking in too many firms, and so the development pipeline is filled with mediocre, low-value projects. Thus a vital facet of a successful new product effort is the development of an idea-generating system. I call this the "Discovery Stage." And there are some specific actions that you can build into your Discovery Stage to generate some breakthrough ideas for new products."

Many other authors have noted this same assumption of idea abundance that has been the reason for ignoring any explicit phases for idea generation in the beginning of product development process. This may characterize correctly the situation of suggestion systems in the context of continuous improvement (i.e., incremental innovation). The general trend toward more radical or breakthrough innovations may be the main motivation for increased attention to the FEI processes and the development of more dedicated FEI models.

In any case, it is really a very big change in the description of FEI, when we transit from the second edition to the third edition. Figure 6 will give you a concrete view about it, when you remember that in the original model this same complexity was implicitly represented with the single box 'Ideation'. Although Cooper does not explicitly differentiate opportunity identification and idea generation, he recognizes the importance of opportunity identification by naming the central part of Figure 6 with 'Great New Product Opportunities'. In other words, Cooper located the opportunity identification activities inside his conceptual box of idea generation (like many other authors have done).

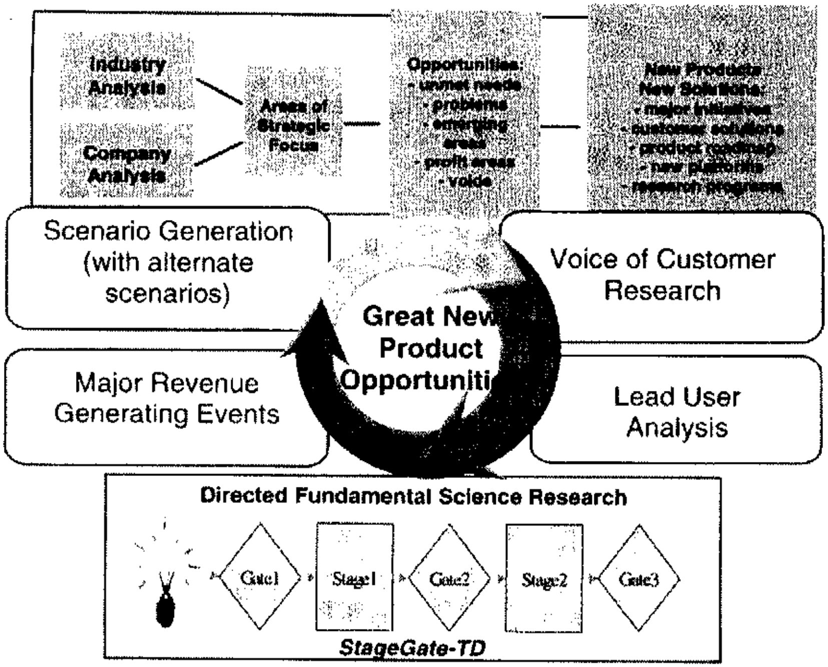

Figure 6. The front end: Stage 0 [Cooper2001, Figure 6-4]

This can be considered as concrete evidence about the conceptual evolution of Cooper's model building and about his changed personal evaluation of the importance of the front end activities in the successful new product development (NPD) process.

2.5 Wheelwright and Clark's funnel models

Wheelwright and Clark also presented in their textbook of new product development a set of funnel models [Wheelwright&Clark1992, Exhibits 5-1, 5-2A, 5-2B, 5-4 and 5-6]. They demonstrate the divergences between ideal (5-1) and actual (5-2A and 5-2B) development funnels, and they present two dominant models (Model I for a large firm: R&D Driven, Survival of the Fittest model (5-4A) and Model II for smaller firms: A Few Big Bets model (5-4B)). Moreover, they recommend Model III called "innovative and focused" that aims to combine and integrate the best features of Models I and II. The most important point in this model is the dramatic expansion of the mouth of the funnel in order to facilitate a more and better idea generation. However their funnels do not explicitly describe any specific details for the supposed set of front end activities.

They have also emphasized the fact that business managers have focused on the later phases of product development, although their greatest opportunities of influence are preset at the front end phases (knowledge acquisition and idea generation) [Wheelwright&Clark1995, Figures 2-1 and 6-1]. This figure is presented twice in this book. This fact is evidence that these authors are serious about the need of refocusing of senior managers' attention. (Note that Miller and Morris have used this same figure in a modified form where 'idea generation' is replaced with 'concept investigation' [Miller&Morris1999, Figure 7.11]

3 Dedicated models of innovation front end

Khurana and Rosenthal's paper can be considered as the most comprehensive study of innovation front end before Koen and others' studies ([Koen et al.2001], p 49). These studies provide us the most dedicated frameworks and analyses of FEI activities. Therefore we will finish our review of innovation processes with these models.

3.1 Khurana and Rosenthal's model

The innovation management provides many challenges for innovations in the domain of innovation itself. Our Project RID is aiming to develop in our collaborating companies such kind of innovation cultures that could produce breakthrough innovations. In other words, we are cultivating the radical innovation capabilities instead of specific radical innovations.

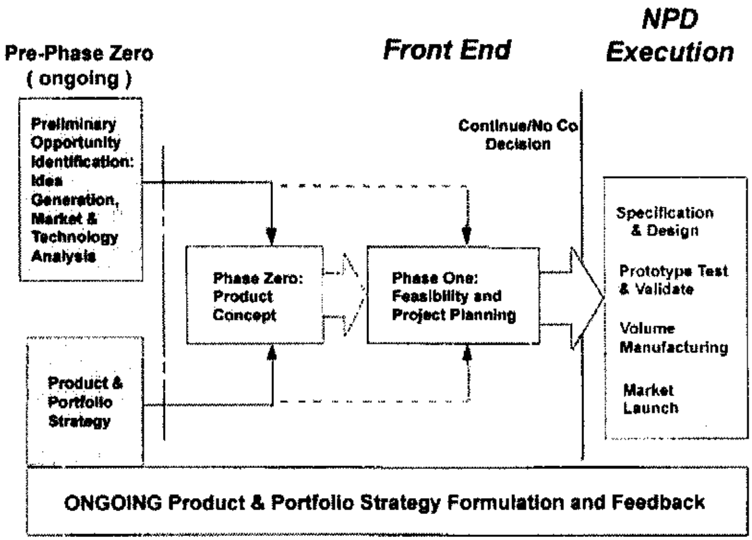

Figure 7. Khurana and Rosenthal's model [Khurana&Rosenthal1998, Figure 1]

Khurana and Rosenthal interviewed 90 product development managers and all of them considered idea generation as an area that needs 'revising' in their companies [Khurana&Rosenthal1998, Note 3]. Because these authors do not distinguish opportunity identification and idea generation, it is impossible to conclude the exact meaning of this 'revising' from their text.

3.2 The New Concept Development (NCD) model

Peter Koen and others have done studies, which focused on the front end of innovation. In order to have a common language and conceptual framework for comparing innovation practices in different companies, they developed the New Concept Development (NCD) model (Figure 8). This model consists of three basic components: engine (including support of senior managers, strategy and culture), influencing factors (rather uncontrollable factors like organizational structure and outer environment) and the inner spoke area (five interacting activities). This model has two entry points (opportunity identification and idea generation) and only one outlet point (concept definition).

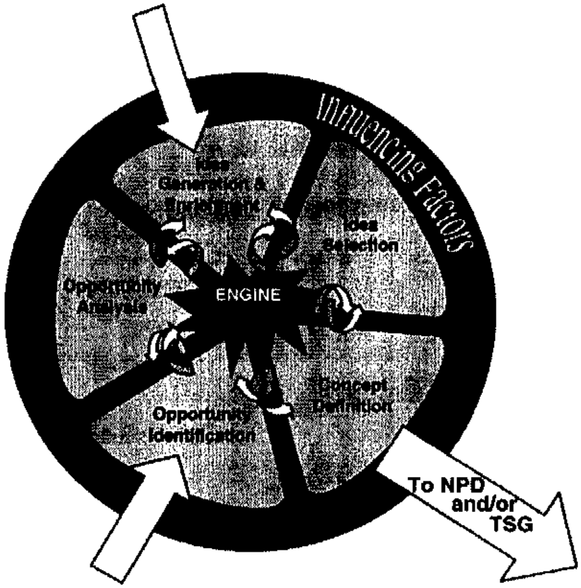

Figure 8. The NCD model [Koen et al. 2002, Figure 1-2].

This model has much richer conceptual sensitivity in respect to the specific types of FEI activities than, for example, Cooper's original Stage-Gate model that refers only to a single box 'Ideation'. Koen and others have also presented the sets of distinct methodologies for each five activities [Koen et al.2002].

Although the descriptions of PCD model emphasize the existence of iterative interactions between all these five elements, it seems to be true that this model presupposes logically a rather sequential process: (opportunity identification & analysis) => (idea generation/-enrichment & analysis) => (concept definition) (see especially [Koen2003]). This conclusion may be warranted by the recognition that their notion of opportunity refers to 'problems' and the notions of idea and concept refer to solutions. And the PDMA's officially accepted definitions of opportunity, idea and concept contain more support for this conclusion [see, for example, [Koen et al.2002, p 7].

Koen and others have also studied empirically the differences of high, medium and low innovative companies in respect to the proficiency levels is respect to the NCD model. We have already find from the Figure 1 that they found no differences in their New Product/Process Development (NPPD) or Stage-Gate processes but statistically significant differences in respect to the New Concept Development (NCD) stage. Figure 9 points out many significant proficiency differences in respect to specific NCD components. One of the three most important differences is associated to the opportunity identification.

We do not consider more these differences. From the perspective of this paper it is important to realize that without a conceptually dedicated and sensitive framework of FEI, Koen and others had not found out these important proficiency differences. In other words, the success of their empirical study was grounded on their appropriate conceptual framework of FEI.

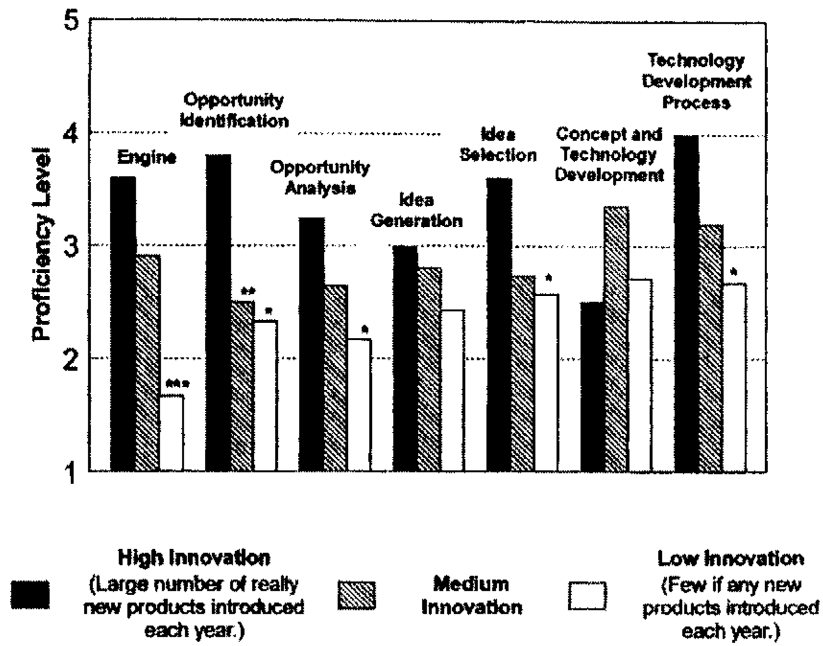

Figure 9. Proficiency differences between high and low innovation companies in respect to different factors in the NCD model [Koen et al. 2001, Figure 4]

4 Conclusion

We want to tentatively conclude that opportunity identification is the logical beginning moment of true innovation. Like in the context of creative problem-solving – or more generically, in the context of genuine question-answering – the activities of question formation (problem posing) logically precede the activities of answering (problem solving). If we view innovation as a specific type of human question-answering (creative problem-solving), it is very easy to realize the fact that opportunity identification is the logical starting point of innovation.

The reviewed models provide us much support for our conclusion. Most of the reviewed models refer to opportunity identification. Although Koen and others' NCD model refers to two entry points, this is not necessarily inconsistent with our conclusion. Idea generation as the NCD model's second entry point can warrantly be interpreted as a reference to a truncated process that starts with some accepted idea proposals generated from the earlier activities of opportunity identification.

Perhaps the most pondering warrant for our conclusion is Peter Drucker's *Innovation and Entrepreneurship* [Drucker1985]. This paradigmatic book of innovation contains many chapters that describe different types of innovation sources as well as the related activities of opportunity identification. You can refer to opportunity identification by using many different words like problem orientation and digging of latent customer needs, but the shared meaning of these apparently different phrases is opportunity identification.

Acknowledgment

National Technology Agency of Finland (TEKES) has supported our Project RID.

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