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A DESIGN PROCESS FOR COMPLEX MECHANICAL STRUCTURES USING PROPERTY BASED MODELS, WITH APPLICATION TO CAR BODIES

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1. Introduction

The objective of the paper is to present an effective process for the design of complex mechanical structures. A multi-objective process for the design of complex mechanical structures is described. The process utilises certain particular mechanical properties that have been identified as central to the success of a design project. A conceptual, mathematical model of a vehicle body is constructed from these salient mechanical properties and the model is then used to generate optimal solutions. In this way, design variants can be explored.

The design process for complex mechanical structures is considered from the conceptual phase to detail design. The requirements for the design are multi-objective and take the form of weight, stiffness, manufacturing, etc., but also the requirements are not fixed and may change. Therefore the design process must be flexible to allow for such changes. A car body is the subject of this paper and its design encompasses all the above considerations. There is a well-established history of car design and manufacture and traditional methods have a strong influence on current practices. The design process described in the paper aims to reduce lead times and not exclude innovative solutions. Shortened lead times may well be achieved by reducing iterative changes during detail design. The development of the proposed design process has been accomplished using the framework for engineering design research presented by Blessing, [Blessing 1998].

The paper is organised as follows. The backround to the problem is described and an overview of the proposed design process given. The proposed process is then presented in a step by step manner using an automotive body part as a design example. At the beginning of each section icons are used to visualise the described steps in the design process, see Figure 1, the focused areas of the process are visualised by solid lines and the areas not concerned have dashed lines. At the end conclusion and future work are stated.

2. Description

The following shortcomings can be identified in the design process currently used:

- Innovative concepts, e.g. ones that use radically different materials or configurations, are often ruled out early in the concept selection process.
- The results from concept studies are not used in an efficient way during detail design, leading to many costly redesigns during the detail design phase.
- Knowledge gained by benchmarking is not used quantitatively.
- Late changes in requirements lead to expensive redesign activities, during the detail design phase.

3. Prescription

In order to pursue a meaningful concept development and selection process, it is necessary to:

- identify the principal assessment criteria.
- measure the performance of the concept model with respect to criteria.
- assess the ‘value’ (not necessarily in monetary terms) that each performance measurement contributes to the total quality of the concept.
- improve the concept with respect to the value judgement to obtain an optimal solution.
- revise the concept model in parallel with the detail design activities.

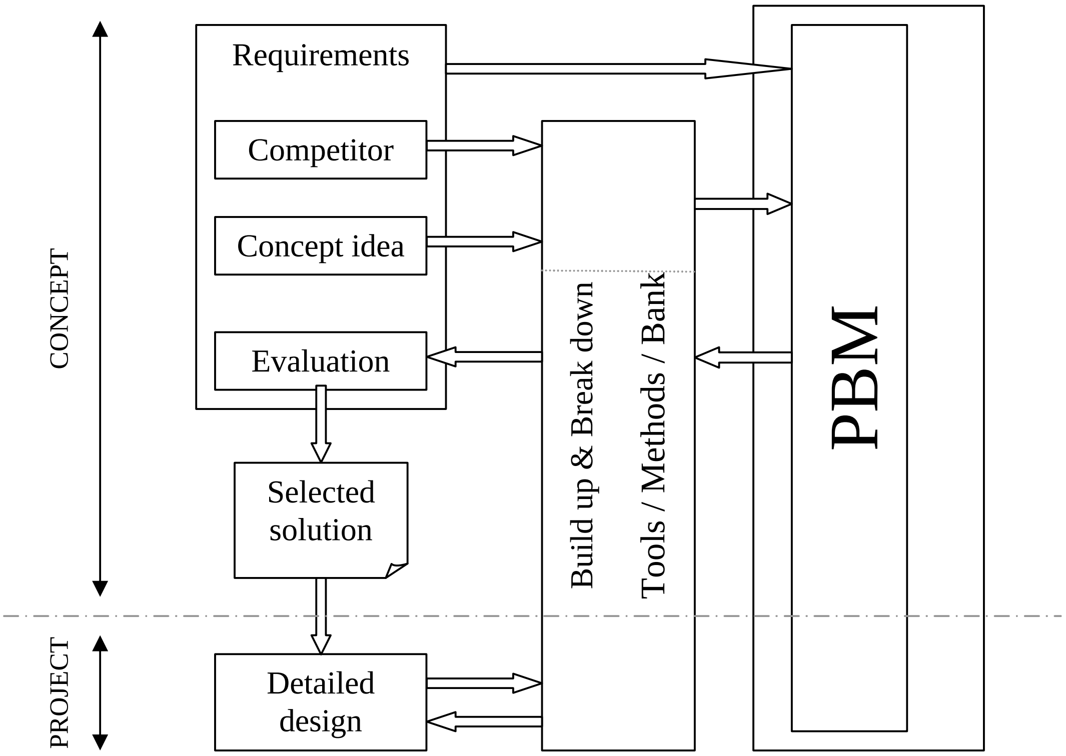


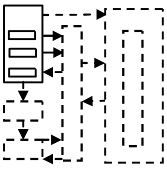
Figure 1. PBM based process for design of complex mechanical structures

Figure 1 shows the design process that is the subject of the present research. It can be seen that the starting point for all projects is a set of requirements (mass, structural integrity, etc.) [Fenton 1996]. A Property Based Model (PBM) is built up for each concept and represents the mechanical and spatial properties of the body concept. The PBM is constructed from organs, [Hubka et al 1988], which represent requirements at a local level. The chosen organs for the car body are beams, joints and panels. In the build up and break down activity, the PBM models are generated for new designs and existing designs from competitors by in-house design teams. A library of organs is used to generate PBM models efficiently; typical elements are beam cross-sections and joint properties. Each project generates new organs and an extensive knowledge bank is created. Such a library is a resource of expertise and so knowledge is readily transferred and the design process is not dependent of particular individuals and their subjective value judgements.

The optimisation procedure normalises the PBM models with respect to key global requirements, e.g. global stiffness, weight, crash worthiness, etc [Hidekazy 2001]. The results of the procedure are used as the basis for comparison of the concepts. The PBM that best fits the quantitative and qualitative criteria is selected. This is an aspect of the design process and is not left to the outcome of any particular design evaluation method. The selection involves the decision-making processes with the company as a whole, and it is important that all relevant parties contribute to, and accept, the outcome of evaluation.

The selected PBM contains all the properties of the model at the organ level. These properties are the guidelines to the detail design engineers. During the detail design phase, the designer is thus provided with quantified solution requirements to meet as decided by the concept PBM that has been selected. The detail design engineer is supported by the computational tools used in the break down phase and can use particular solutions from libraries. Local changes required at the later stages of design can be considered objectively by the detail designer. The changes can be tested against the solution requirements (stiffness of the subassemblies, etc.) and if the requirements remain satisfied then the change can be met.

4. First step; Requirements



The steps in the proposed design process are exemplified by the design of an A-pillar, see figures 3 and 4. The first step in any development process is to state the requirements [Pahl and Beitz 1996] on the system to build. The requirements on a car body are numerous and often contradictory. One requirement affecting the A-pillar, is the American roof crush legal requirement MVSS 216, see figure 2.

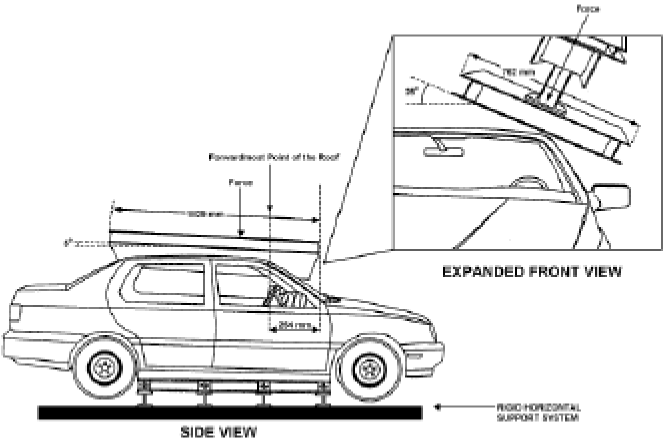


Figure 2. American roof crush legal requierements MVSS 216

4.1 Competitors

In the presented process competitors having properties close to the targeted market segment are chosen. These competitors give hints and ideas on how to design a car body fitting the chosen market-segment. The process of examine competitors is called benchmarking, see [Andersen 1996]. Benchmarking can be done in many areas and levels, such as business strategy, marketing strategy as well as on the product itself. Benchmarking of competitors product was used by Xerox and permitted them to gain in competitiveness, also in our process product benchmarking is used.

4.2 Concepts

Concepts are developed based on the requirements and results from benchmarking, the concepts can be of different level of detail, from sketches on a napkin to a CAD drawing. Since European car manufacturers built the first self supporting car body (Uni-body) this type of structure has been the dominating structure with the few exceptions mainly being sports or luxury cars in small series. The self supporting car body, where sheet metal stampings are spot welded together to form integrated beams, joints and panels may be a good way of building cars but it can also act as an fictitious constraint [Pahl and Beitz 1996] impeding designers to think of new solutions. Furthermore concepts based on self-supporting structures will because of the deeply rooted experience of this technology have behaviour near their optimum, the design process has therefore to be able to handle this bias.

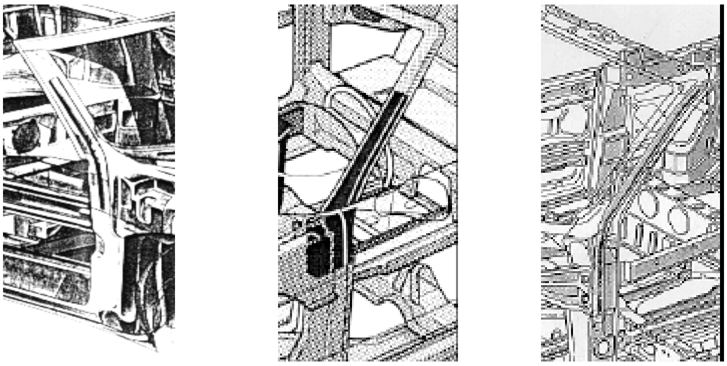


Figure 3. Three different A/pillars from competitors, used for benchmarking

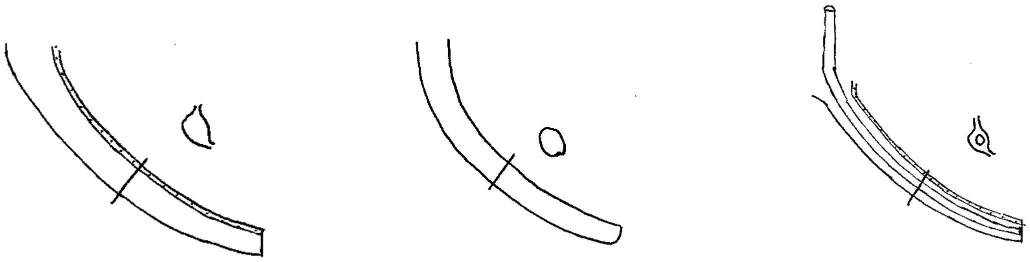
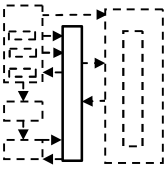


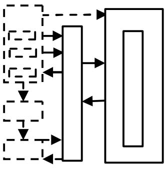
Figure 4. Three concepts for the A/pillar. From the left/hand side, stamped and spot welded boron steel, hydroformed steel and finallz stamped steel with an interior reinforcement tube made of boron steel

5. Second step; Break down



The chosen competitors and the concepts developed are broken down into manageable quantities and objective information. This enhances comparison between different concepts and competitors. For an A-pillar this information is the shape of the middle line of the beam and the section. By cutting the competitors A-pillar into slices and using the in-house software DAMIDA, figure 5, the sectional properties can be found. The sections of the concept ideas can be analysed in a similar way. The results of these analysises are put into the knowledge bank. And used for creating the property based model, PBM, see figure 5, and reference [Bylund 2001].

6.Third step; Optimisation



By using the intermediate stage of organs, principal function-carriers are identified without restricting detail design. The model built up of these organs is called PBM and it links requirements from global to organ level. This solution independent representation enhances new designs by limiting fixation, [Pahl and Beitz 1996]. The generality of these organs is put on a level where they give sufficient information for carrying out detail design but without biasing it. Using the same metrics for all PBMs, beam parameters, joint parameters and sheet parameters, enhances the selection of PBM. For an A-pillar the metrics are sectional properties such as Ix, Iy, Iz and moment capacity.

A tool for optimisation of frame structures has been developed to handle the optimisation step in the design process, see figure 6. This tool can handle booth beam and joint organs and in the future also panel organs. Multiple load cases can be used and also separate mass constraints for beams and joints or one mass constraint for total mass.

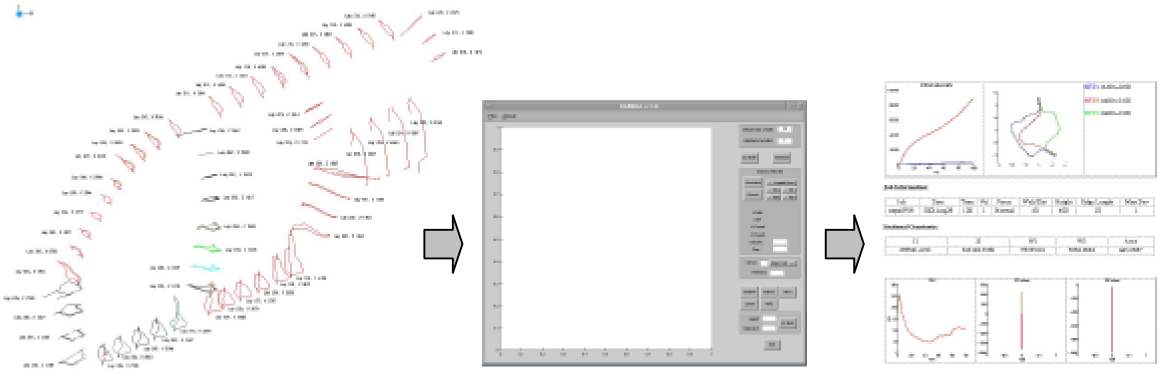


Figure 5. Brake down process. Acompetitor or a concept is sliced and the sections numbered and analysed with the software DAMIDA. Knowledge of the section capacities is gained and put in the knowledge bank

The input to this tool is the PBM model defined by

- Topology
- Material
- Masses
- Beam section properties
- Joint stiffness

By use of this data an optimisation model can be developed for each concept and competitor or directly from requirements. As an example, the basic topology for a A-pillar is shown in figure 7a and the optimised beam sections can be seen in figure 7b. In the initial design all beam segments had the same cross section properties and after optimisation one can see that the allowable material have been distributed in an optimal way between the different beam segments.

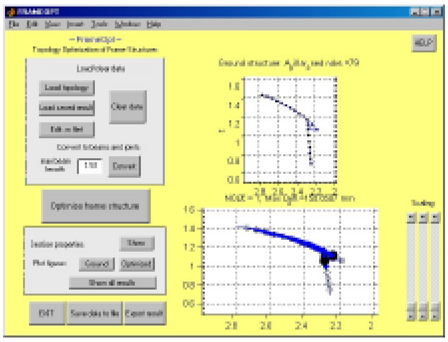
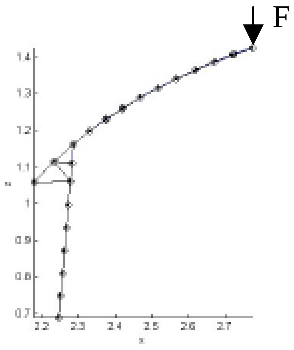


Figure 6. Optimisation tool



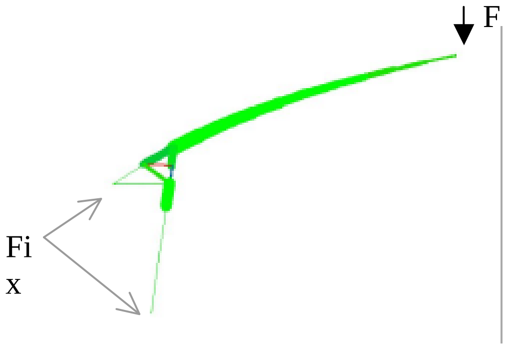


Figure 7a. Basic topology **Figure 7b. Optimised structure**

The result of this is a structure with the stiffness increased by 2.7 times with respect to the initial design, the maximum deflection can also be found. The optimal diameter varies quadratically with the distance, *x*, for the upper part of the A-pillar as in figure 8. This is the real objective potential for that concept based on its topology and mass. The same is done for all concepts, competitors and requirement based models. In the A-pillar optimisation all these models would have the same mass but different performance in stiffness. Another possibility is to set maximum allowed displacement and minimising mass. This results in structures performing equally but with different masses. If the structure is build up by beams and joints the program can also be used to optimise joint stiffness in a structure. This is a good way to get information of how to build the different beam connections existing in the structure. An example of such a structure is the 3D-console beam seen in figure 9 where beam properties and joint stiffness has been optimised simultaneously. Two load cases have been used in this optimisation. The size of each sphere is proportional to the stiffness for that joint.

By optimising the PBM models for minimum weight and given deformation or maximal stiffness for a given mass all concepts are normalised and are at the edge of their performances. This enables a fair selection process between the different PBMs.

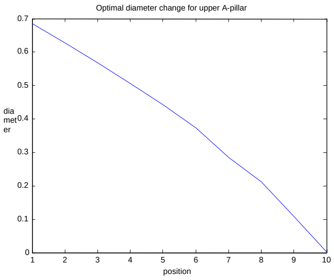


Figure 8. Diameter

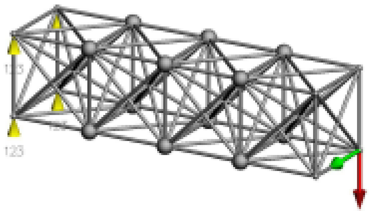


Figure 9a. Ground structure

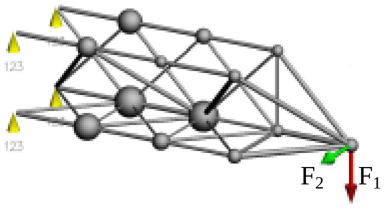
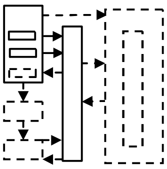


Figure 9b. Optimised frame structure

7. Fourth step; Build-up

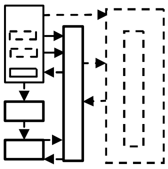


When the PBMs are optimised they need to be built up with a technical solution in order to get sufficient information for the evaluation. This stage can be seen as the embodiment design stage in [Pahl and Beitz 1996]. The built up stage is done with the same tools as the break down stage, furthermore results from break down such as competitors beam sections can be used as inspiration, this way the break down and built up works as the knowledge bank discussed previously. In our example three different technologies where chosen in the build up stage of the A-pillar, see figure 4. A bent boron steel tube with constant section covered with sheet stampings welded together, two stamped boron steel sheets spot-welded together to a tube with varying section, and finally a hydro formed steel tube.

All these concepts should respect the same PBM's quantitative mechanical requirements such as Ix, Iy, Iz and moment capacity. In the evaluation stage presented later, these concepts are compared mainly with respect to non-mechanical requirements such as price, manufacturability, aesthetics and environmental since they have already been normalised with respect to mechanical requirements. During the build up stage it was found that the alternative with an interior steel tube covered with stampings could not reach the mechanical requirements therefore this concept was rejected already during the build up phase.

8. Fifth step; Concept selection and Detail design

8.1 Concept selection



The design literature contains many references to specific methods that can be used to choose between alternatives [Pahl and Beitz 1996, Pugh 1990 and Cross 2000]. These methods are suitable for use at different stages of design, e.g. ideas, concepts and detail design and for different types of criteria, e.g. quantitative, qualitative, subjective and objective. It is important to use selection methods appropriately otherwise choices can be made in error. For example, it is not a wise approach to select concepts by guessing performance scores with respect to criteria that can only be evaluated when much more detail is known.

Commonly, design alternatives are considered at the conceptual stage by a general qualitative review of a broad spectrum of criteria followed by more detailed analysis of a reduced set of options that has been chosen for further consideration. This process can be unsatisfactory. Good options can be eliminated because of personal preferences, there may be uncertainty concerning the benefits of certain options or lack of experience may bias judgement. Such problems can be avoided in concept selection if the key parameters can be identified that can be used to generate potentially optimal concepts using high quality information.

The use of property based modelling and optimisation normalises all concepts by putting them on the edge of their mechanical performance. Only the concepts that fulfil the quantitative mechanical requirements continue to the concept selection step, this reduces the option choice. In order to make a final selection, qualitative criteria such as surface treatment, weldability etc. need to be considered. However, since the number of options has been reduced, each qualitative criterion can be considered in depth.

Topology, material properties, mass, sectional properties and joint stiffness were used in the optimisation stage of the process. The task is now to consider the two concepts that fulfil the mechanical requirements and compare them with respect to a range of qualitative criteria. The concepts are:

- two stamped boron steel sheets spot-welded together to a tube with varying section
- a hydro formed steel tube

The following criteria were identified as being important in the qualitative evaluation process:

1. Cost
    1.1 Investment
    1.2 Production cost

2. Production: risks associated with the following operations.
    2.1 Welding
    2.2 Assembly
    2.3 Tolerance
    2.4 Surface treatment
    2.5 Lead time/ production capacity.

3. Attachments: risks associated with the following
    3.1 Windscreen
    3.2 Interior trim
4. Styling freedom

Paired comparison analysis, in which the concepts are compared to each other with respect to each criterion is an appropriate method to evaluate these concepts [Pugh 1990]. Engineers were consulted who were expert in the relevant fields and, from their judgements, it was possible to complete the concept evaluation table. The concept consisting of two stamped boron steel sheets spot-welded together to a tube with varying section is used as reference. Table 1 shows the results of the evaluation. In the table, a '+' sign means that a concept is better than the reference concept with respect to a particular criterion, a '-' means worse than and an 'S' means no difference (or cannot judge).

Table 1. Paired comparasion analysis

CRITERIA	CONCEPTS	
	Stamped spot welded boron steel sheets	A hydro formed steel tube
1. Cost	Reference	
1.1 Investment		-
1.2 Production cost		+
2. Production: risks associated with		
2.1 Welding		+
2.2 Assembly		S
2.3 Tolerance		+
2.4 Surface treatment		+
2.5 Lead time/ production capacity.		S
3. Attachments: risks associated with		
3.1 Windscreen		-
3.2 Interior trim		S
4. Styling freedom		+
Σ +		5
Σ -		2
Σ S		3

From table 1, it can be seen that the hydro formed steel tube concept emerges as a favoured concept. The next stage of the process would be to investigate the negative aspects of this concept to ensure that no insurmountable problems will be encountered and to undertake more detailed work on these and other aspects of the concept.

8.2 Detail design

When a concept is selected the project phase starts and detail design is launched. Teams of design engineers do the detail design. They are supported by the break down build up tools and the knowledge bank. The knowledge bank should be used for tips during detail design and not as an exhaustive list of what designs are permitted. Seeing the bank as an exhaustive list has a negative impact on the design process augmenting the fixation, see [Pahl and Beitz 1996] and impeding the possibility for optimal designs. By using these easy to use tools, e.g. DAMIDA detail designers can continuously compare their design against requirements at organ level. The knowledge gained during the concept phase will therefore survive and contribute to the success of the final detail design. Costly loops of complete car body simulations will be reduced.

9. Conclusion

The proposed process has the potential to both speed up the development of complex mechanical structures while at the same time enhancing innovative solutions. This is done by stimulating a more solution independent approach where a function structure of organs called PBM represents the behaviour of the car body.

Several easy to use tools that do not require expertise in CAE-analysis are used to evaluate the performance of organs. The tools are used both during the concept and detail phases. The tools generate a bank of knowledge of the salient engineering features of organs which makes the development process less dependent on the subjective interpretation of particular individuals. The concept selection process is both efficient and clearly objective. Concepts that do not attain essential performance requirements are rejected at an early stage. In-depth evaluation of concepts focusses on thos concepts that have attained an optimium performance for their generic type. Qualitative evaluation, which involves extensive investigations, is only carried out on concepts that can achieve the required performance criteria.

Breaking down all proposed concepts to organ level makes comparison easy using parameters of the same type. The same tools are used to break down design proposals for analysis as are used in embodiment and detail design, therefore the process is efficient and creates a learning design environment.

Concept selection processes such as that described in section 8.1. are not without their problems. It is difficult to ensure that all departments and groups within a company accept the decision and it is not unknown for concept selection decisions to be re-visited later, which is wasteful of time and effort. In order to select a concept that is acceptable throughout the organisation, it is important not to let some poor characteristics be masked by other positive characteristics. It is possible for a multi-ctriteria concept selection method to identify certain concepts as being very good because a negative with respect to a particular criterion is compensated by a number of other posisive assessments. E.g. a selection method that results in a light, strong concept but which also has a very corrosion sensitive surface will not be welcomed by people at the surface treatment department even though that concept has the largest number of positive characteristics. Another way to take decisions is required.

10. Future work

A better way could be *not to* place emphasis on any particular method(s) as the leading approach to concept selection, but instead to clarify and strengthen the decision-making processes used by a company. The principal point is that all key departments, from aesthetic styling to manufacture, should own the decision to adopt a particular concept. For such a sense of ownership to be established, departments need to have a greater involvement in the concept selection process. This means more than commenting upon the merits and de-merits of particular concepts at some stage so that a particular selection process can be used.

Involvement by all is required throughout the concept development process from the first stages. It is beyond the scope of this paper to pursue this line of thinking in depth, except to comment briefly on future research activity in this area. The decision making paths need to be understood: at what stage are decisions made, who makes them, are there powers of veto? These questions require answers based on realism, not idealism, and must encompass all levels of company decision making. Also, concerning the integration of diverse departmental interests, there are certain guideline principles that are well established which might be usefully employed. Multi-disciplinary groups can be very productive when their work is directed using creative problem solving principles. Divergent thinking with suspended judgement coupled with objective convergent thinking helps to identify potential problems, to generate solutions and to gain acceptance of the decisions by all interested parties.

Good decision making in concept development relies on the use of clear decision making processes which include all departments in a meaningful way, supported by objective methods such as property based models.

Acknowledgements

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