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AN INDUSTRIAL CASE STUDY OF DESIGN METHODOLOGY AND DECISION MAKING FOR AUTOMOTIVE ELECTRONICS

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ABSTRACT

The growth rate of R&D activities in automotive industry brings an increased need for transfer of design knowledge. This, in combination with growing complexity of the product puts new demands on the decision process. In this paper, decision methods used within the R&D department of an international vehicle manufacturer has been investigated through interviews and surveys. The main focus has been to identify and analyze methods used by the individual roles within different development teams. The survey reveals that a majority of the respondents use unstructured methods for resolving decision issues. When respondents were asked about their preferences there was an expressed need for more structured methods.

Among these, two methods are elaborated that are well established within the product development process: expert support and guidelines, but also on methods training in general. A third conclusion is to redirect the current decision process to build on more structured methods through training.

This work has contributed also by identifying the company best practice. The long term goal is to have all development teams adopt one common development process at the team level.

1 INTRODUCTION

To stay competitive in the automotive industry vehicle manufacturers are forced to release new models more often. At the same time the product portfolio must be further diversified in order to satisfy individual customer demands. The shorter development cycle and increased number of concurrent models brings an increased need for transfer of design knowledge.

Today most innovations made within the automotive domain are driven by electronics. A study made by Mercer Management Consulting and Hypovereinsbank in 2001 [15] claims that the total value of software in cars will rise from 4% to 13% by 2010. According to a more recent 2006 study made by McKinsey [7] they expect the total value of electronics in automobiles to rise from the current 25% to 40% by 2010. One of the reasons for the high cost of electronics is the large number of Electronic Control Units (ECU) used. The trend in the car industry is currently changing, but there has been a philosophy of "one function – one ECU".

1.1 AUTOMOTIVE ELECTRIC AND ELECTRONIC SYSTEM DEVELOPMENT

The embedded software development within the automotive industry is not very different from other embedded systems. The automotive embedded systems are characterized by being a mechatronic system which adds complexity. The systems are often resource constrained and trade-offs between the system behavior and the resources required is of great importance. Cost, time-to-market and quality are the most important factors. The growing number of interconnected sensors, actuators and functions allocated to different ECUs has led to a need for standardization to simplify the development process.

The studied company is an internationally well known vehicle manufacturer of commercial vehicles and should be representative for the rest of the industry. It has managed to achieve sustainable and profitable growth and it is interesting to study which factors that contribute to the success. The current and future growth rate of its R&D organization (Figure 2) brings an increased need for transfer of design knowledge. This, in combination with growing complexity of the product puts new demands on the design decision process. In future development projects it will be necessary to handle an increasing amount of information. It is critical that the decision making process is up to date with the fast changes of the

product design. The growing demand for decision support tools is of special interest.

1.2 OBJECTIVE AND DELIMITATIONS

The main objective of this study is to examine the decision making process within electric/electronic system development. The aim is to gain knowledge on where the company stands today and how the decision process can be further developed.

The studied manufacturer purchases about half of the systems from external suppliers. The study requires detailed information about the design process and relevant results are best achieved by focusing on systems that are internally developed. Three systems were studied; the engine management system, gearbox management system and the main vehicle controller. Those systems were chosen because of their differences in size of the developing organization.

The overall decision process includes roles at every organizational level. However, in this study only decisions made by persons that work as, or close to system developers, are considered. The decision process at levels above the development team is not regarded.

1.3 PAPER OUTLINE

In the next section, the method used to obtain information about the design decision process is described. This is followed by a literature survey on structured methods that are available today. Empirical findings are then analyzed according to a general decision model, in order to identify current weaknesses and potential improvements of the design development process. Finally three conclusions are drawn from the analysis
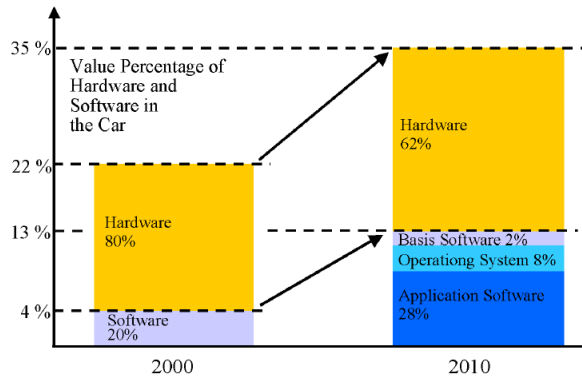

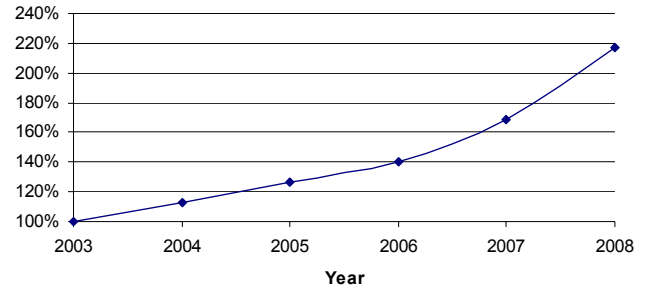**Figure 1 Value of hardware and software in cars [15]**

Figure 2 The increase of number of employees working within the system development organization expressed as a percentage compared to 2003.

2 METHODOLOGY

The information needed in the study was gathered in three steps.

1. A document study was carried out to investigate and understand the impact on the development team of the formal decision process at levels above the development team.
2. A number of interviews were conducted to study how decisions are made and with what requirements available. Only decisions made by persons working close to system developers were considered in this part.
3. With the knowledge collected during the document study and interviews a web survey was conducted. This was done to verify the common statements found during the interviews.

These steps are described in more detail in the next subsections.

2.1 DOCUMENT STUDY

Product design specifications are stored in databases and are historic documents. Decisions are often documented in meeting minutes and similar documents. Those documents are therefore a valuable source of information which the content analysis of the document study will gather. All minutes of the monthly technical specifications meeting have been reviewed on decisions with a direct impact on the electrical system. The structure and content of the main engineering change order (MECO) and engineering change order (ECO) for one of the studied systems have been reviewed.

2.2 INTERVIEW

Three different roles within system development where investigated using semi-structured interviews. The system owner is provided with the overall responsibility of the development of the ECU hard and software. The object leader is responsible for planning and follow-up of all development activities within the system. The object leader allocates resources necessary to reach the main deliverables requested at each phase transition. The function owner supervises

development of the many part functions allocated at different ECUs. The development engineer is responsible for code in different part functions belonging to one system and, thus, is working closely with several function owners.

Each respondent was interviewed during 60-90 minutes. Answers were recorded in writing without the use of audio equipment. Respondents were assured anonymity and received their answers in writing after the interview. The first part contained process related questions in the form of a case study. The respondent was confronted with four cases, each designed to represent a scenario with a (small / large / expensive / difficult) decision. The four cases were visualized on paper. The second part contained questions related to design methods. The interviews were summarized together with feedback from the respondent.

2.3 SURVEY

The interviews were supplemented by a web survey. The survey, based on a subset of the interview questions, was sent to the corresponding roles (system owner, object leader, function owner, and developer) within all systems. The web survey was sent to 150 engineers at R&D. They were asked to answer the survey within one week. After the first week 36 persons had responded. The final response frequency amounted to 64 persons. Of these 28% worked as system owner, 21% as object leader, 40% as developer, and 11% as function owner.

Results from the web survey were analyzed in Statistica [21]. Correlations were investigated through regression analysis and filtered at the 90% significance level.

2.4 VALIDITY

Construct validity ensures that the studied artifacts can be applied to analyze this exact problem [25]. Threats to construct validity are for instance that the documents available for the document study can be partial. By triangulation of the information with interviews and the web survey construct validity can be ensured. The documentation of the interviews is also reviewed by the informant. The working experience of the authors will also help to ensure construct validity.

Internal validity ensures that the conclusions we draw from the web-survey is the only possible one and have not been affected by another possible cause [25]. Internal validity is ensured by doing pilot interviews with informants similar to the ones questioned in the study. The questions can thereby be altered to ensure internal validity. The respondent should not be biased by how questions are phrased. During the interviews it was important to avoid the use of formal words like "method" or "process". Respondents were rather asked to describe their process in their own words. Two questions were rephrased after the third interview.

External validity is the degree to which the conclusions in the study would hold for other organizations and at other times [25]. The major threat to external validity is the degree to which the conclusions would hold for other companies. A major part of the research was done within the company. It is

therefore important to study theory and analyze related work from other areas to prove its validity.

Reliability is about minimizing faults and biases in a study and to make the result repeatable [25]. Reliability is ensured by well documented and planned interviews.

3 THEORETICAL FRAMEWORK

Decision making under uncertainty is influenced by a number of factors [11], and some of them lead to less rational decisions. One of many social psychology factors is the anchoring effect. The anchoring effect describes how your initial guess or starting point relates to your final answer. The mind creates an imaginary point of reference.

Another problem when making decisions is that one might be influenced by previously made decisions. This might lead to a bias in the review of some alternatives. An important factor in this case is the so-called sunk cost, which describes how our decisions are influenced by previously made investments in such a way that one bad investment decision is often followed by a new bad one in order to justify the first decision.

To make a decision many types of information need to be present. The model presented in Figure 3 shows how the different types of information can be related. An issue states the problem encountered which is defined and limited by different criteria. A criterion limits the design space and the number of feasible alternatives that can address the issue. During the evaluation the alternatives are measured relative to the criteria and leads to a decision. The evaluation of alternatives can be done by using one of the structured methods presented in next section.

ISSUE   CRITERIA   ALTERNATIVES   EVALUATION   DECISION

Figure 3 A model for the information flow of decision-making [23].

4 RELATED WORK

There are many structured methods available. Some examples mentioned in industry surveys [2] are Pugh evaluation matrix [18] and the analytical hierarchy process (AHP) [19]. A comparison of methods specialized towards software architecture analysis [5] has found Architecture Trade-off Analysis Method (ATAM) [12] to be the most suitable. The Cost Benefit Analysis Method (CBAM) [13] is an extension of the ATAM and uses the quality attributes from ATAM but also consider cost when reasoning around the most suitable architecture.

In a study of 46 companies made 2005 in Finland [20] it was shown that the most commonly used (76%) concept selection method was concept review meetings. About half of the companies used informal methods like checklists, intuitive selection or expert assessment. Less than one out of four companies responded to use one or several formal methods.

The explanation to the low usage of formal methods is that they are hard to fit into the industry. The proposed solution is to present success stories and to further investigate the need of the industry. A survey has also been made on the UK industry [2] and showed similar results. An article published in Journal of Engineering Design attempts to answer the question, why does industry ignore design science [6]. The article claims that industry solves problems by using the knowledge of experienced engineers, which is often faster than using a structured method. One of the presented answers is that many structured methods require information which is often not present or very resource consuming to generate.

Ken Hurst [8] presents the following reasons why a structured method should be used:

- Time wasted in pursuing wrong alternatives to the detail design stage is avoided.
- Causing decision-making to be visible helps ensure the process is repeatable.
- The ability to evaluate the thought processes of others is developed.
- The designer can defend decisions made in discussions with managers or clients.
- A designer with no previous experience can carry out a sensible evaluation of alternative concepts.
- The process of concept selection stimulates new concepts or encourages combination of concepts.

Ulrich and Eppinger [24] present a similar list of benefits and emphasize that the use of a structured method provides customer focus and a more competitive design. The way structured methods encourage knowledge transfer is also stressed by Liker [16]. He points out the difficulty to transfer tacit knowledge compared to explicit knowledge. Explicit knowledge such as mathematical equations and historical facts are often more easy to store. Tacit knowledge is often more diffuse similar to what is taught through apprenticeship. Toyota creates their learning network through activities such as technology demonstrations, checklists, know-how databases, mentoring and lessons learned [16].

5 EMPIRICAL FINDINGS

In this section, results from the document study and the investigation on the process in the development teams are presented. Together with the document study the product development process is described.

The current official process for decisions in the company is described in an internal standard. In this document it is stated that "The success of the assignments in the product development process requires among other things a clear decision structure." It is noted that the embedded software development process is slightly different. Here the important principle is expressed as "in each development stage, the software shall be documented in such a way that a new programmer is able to develop the next release further". An earlier development model for embedded software ("checklist

for designers") however, is now replaced by a general checklist for designers.

Trade-off curves, guidelines, checklist are used in different departments and projects. Trade-off curves are being used frequently in part of the development process. Much knowledge is stored in guidelines and a new effort has recently started to gather all design know-how into one database.

There are also various training courses offered; decision making and problem analysis, modularization, ECU-system and functional concept design.

General aspects of the decision process of the company is defined and well documented as described. Yet, knowledge about the process is poor. Insufficient knowledge has two interpretations, either confidence in the product development method is poor or simply there is a lack of education. Respondents thought there is a correct answer. Evidently, the interview participants recognize there is formally a correct way of how to perform the selection of alternatives. The expressed need for structured decision methods is contradicted by the poor knowledge. Education can bring better understanding and improve performance of existing decision meetings and on how decisions should be communicated.

5.1 DOCUMENT STUDY

From the investigation on the minutes from project meetings it is noted that only a small fraction of the decisions made concerns system development. Instead, it was evaluated if decisions could be traced through the ECOs. ECOs related to one system were reviewed and was found that only in a few cases, introduced changes are referring directly to a decision point. By tracing the ECO back to the main ECO the project decision is found. Normally the changes made in individual ECOs are not easily derived from project decision point referenced to in the MECO. The small influence of the project meeting on individual decision points in the daily work of system development is confirmed in the interview results.

### 5.2 INTERVIEWS AND WEB SURVEY

The web survey contains a subset of the interview questions. Results from both studies are reported together. In general the respondents were familiar with the issue of concern. Many of them had prior to the interview thought about shortcomings of the current decision process. Several participants responded by asking whether their answer was correct or not. In other words there is a common belief that in each case, there is a formally correct way of how decisions should be handled.

Several aspects of the decision process are covered in the interviews and the survey. Potential improvements of the decision process extend over all the investigated aspects. The IBIS model [23] was chosen in order to develop well-defined solutions that are easy to implement. The model is mainly used to organize the results and the analysis in a similar way. In the following, findings from the interviews and survey are presented referring to the IBIS model.

5.2.1 ISSUE

A decision issue is a call for action to resolve some question or a problem [23]. This topic was divided into two questions, of which the first handles information flow and the second handles the action performed to resolve the questions.

The result from the survey is illustrated in Figure 4. Here developers generally answered that they learned about changes from other developers or system architects. Object leaders and system owners gave no solid picture about the origin of information. System owners answered that they receive information through a variety of channels, some of them even from all channels. This is consistent with the representative role of the system owner. He should be ambassador of the system but all system owners should receive information through the same set of channels.
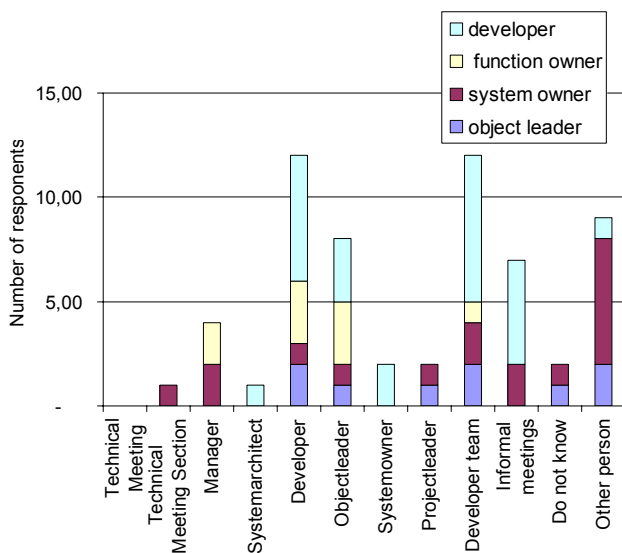
Figure 4 Information channels: the bar graph shows from where developers/function owners/system owner/object leaders receive information about changes on their system.

In several cases respondents indicated that there was much confusion about the information flow. In one answer it was commented that "information is received through all channels and it is a real mess". In one case it was also mentioned that rumors about decisions made have negative effects and could cause panic.

From the interviews it is noted that decision issues are raised effectively within the engine and gearbox system development teams, much owing to a recently adopted Rational Unified Process (RUP) [10]. RUP is an iterative software development process which has been adapted to suit embedded system development. In their event management system actions are handled in two steps. Development engineers enter new ideas to solve a problem and then prepare a detailed solution which is presented at the architecture decision meeting. The event management system keeps the designers updated on a daily basis and takes the role of primary source of information.

There is some confusion about how development work is related to the project meetings. According to the formal process, there are three conditions, each one individually sufficient, to raise a decision point to the project level. It concerns the project meeting if there is a change in technical specification, change in driver environment or change that will have impact on customer choice or on the market organization in any other way. During interviews only two respondents were able to identify one necessary requirement for a decision to be raised to the project level.

As a consequence of limited knowledge about conditions for PM, issues inevitably will fall between chairs. Further employees expect information to be distributed from the project meetings. When this does not happen, requirements will be regarded as unclear. The level of detail in the decision points at the project meeting should be harmonized. It must always be evident why a certain issue is raised to the project meeting and also why decisions made have a certain level of detail. Further, training about the project process, and specifically decision paths, must be emphasized.

Our observation that developers receive information primarily from other developers or team of developers and from informal meetings is consistent with the theory of the global village [4]. In the village no resident is independent of other actors. In a vehicle all systems are interfaced physically through a CAN network and logically through distributed functionality. Thus, the design work is directly affected by changes in neighboring systems as well as company external factors.

Potential improvements within the issues stage in the IBIS model are related to the observation of a large number of information channels. To reduce the number of information sources it is important to promote one source as reliable and showing endurance. Such a source will gain trust among those who depend on its information. From this rather limited study it is noted that the way of working differs significantly between individual development teams. The successful use of the event management system and the change control board (CCB) keeps the designers updated on a daily basis and takes the role of primary source of information.

5.2.2 CRITERIA

The criteria limit solutions raised by an issue [23]. Among developers a majority experience that design requirements are unclear or do not exist. This is shown in Figure 5. Object leaders and system owners believe that the level of requirement specification is sufficient.
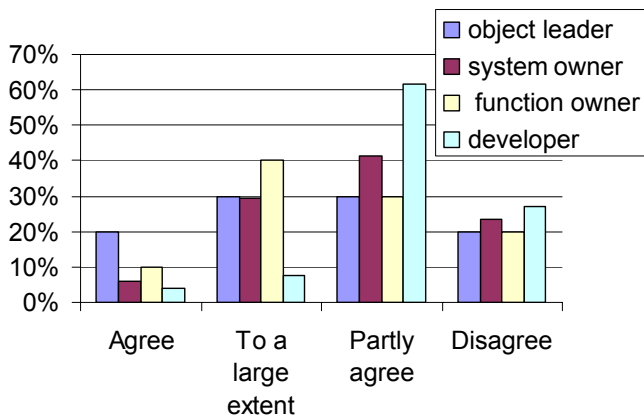
Figure 5 The percentage of each role that answered to the question how well the statement "Our design requirements are clear" corresponds to current work.

Respondents answering that requirement do not exist correlates 0.63 with those who prefer expert support while the group who find requirements unclear correlate to 0.72 with those who evaluate more than one solution alternative.

The general shortcoming of the requirements specification handling process indicated in interviews as well as in the survey can be divided into three basic needs.

- Requirements must be specified early in the process
- Tools for handling requirements are needed
- The responsibility for requirement specification must be clearly allocated to specific roles in the organization.

5.2.3 ALTERNATIVES

An alternative is an option generated to address or respond to a particular issue [23]. In several cases more than one solution concept has been developed. Often one solution is already implemented and the improved solution makes an alternative. But in some cases only one alternative is feasible.

The handling of design alternatives differs between individual groups of staff. From the survey it is noted that the use of multiple design alternatives is predominant among engineers with 3-5 years experience of system development. This is shown in Figure 6.
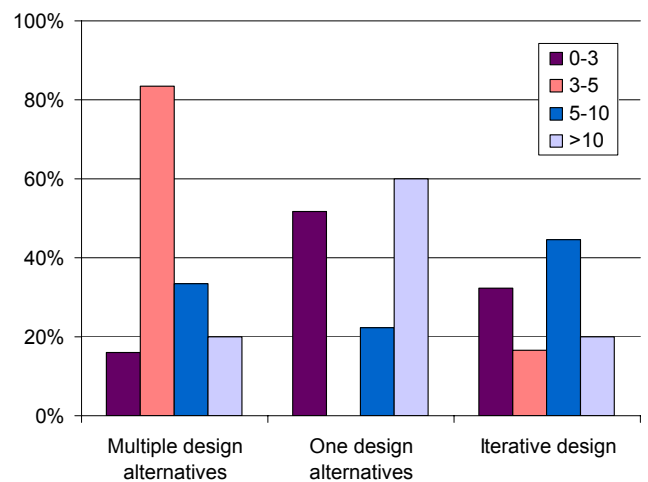

Figure 6 The relation between number of alternatives and years of work experience. Use of multiple alternatives is predominant among employees with 3-5 years experience.

The observed tendency that novice designers only use one alternative supports the idea of method training for new employees. The training should cover advantages of parallel development lines, which is necessary to produce alternative solutions. The need for training is not limited to just the newly employed but should rather be viewed as a continuous process where at least one member of each team is further educated each year.

5.2.4 EVALUATION

Evaluation is the activity of argumentation supported by information developed through prior knowledge, analysis, experimentation, or information gathering (e.g. expert advice) [23]. Respondents in general acknowledge the use of unstructured decision methods (Figure 7) but on the other hand emphasize the lack of structured decision methods. Among structured methods, expert support is most commonly used today. This method is also the most preferred together with checklists. The system owner role correlates strongly with preferred structured methods (formal design review meeting 0.59, checklist 0.55, expert support 0.66; rating however, is not correlated).
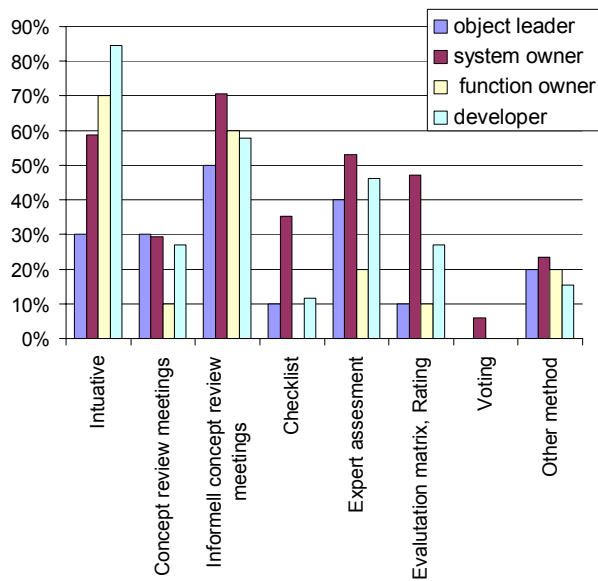
Figure 7 Current use of evaluation methods within each role. The present process is dominated by unstructured methods.

Expert support is provided by the technical career, which is an acknowledged career alternative within the company for those who has chosen to become experts in their field of work. The career starts as engineer and an experienced engineer can then be promoted to senior engineer. The highest level of the career is technical manager and senior technical manager which are positions. The analysis has shown a need for support in methods and technology, especially for the recently employed engineers. According to the role description a senior engineer should be able to educate and coach other engineers.

A question in the web survey about what structured decision methods are used today, strongly correlates with the use of multiple alternatives in question 10. At the 90% significance level correlations with the use of more than one solution alternative were 0.55 (checklist), 0.55 (expert support), 0.6 (ranking method), 0.79 (formal design review meeting).

Among those who use iterative design as a method for development the majority has worked 0-1 years. The group is evenly spread between departments but correlates strongly (0.60, 9 of 13 respondents) with the perception of insufficient requirement specification. There is a strong correlation between engineers with 3-5 years of working experience and those who use several alternatives (Figure 6).

One development team illustrated how alternatives are evaluated on the basis of three architectural principles:
- simple is best
- smallest number of variants
- minimal interface between modules

From the interviews and the web survey the need of structured methods has become evident. From an organizational point of view new roles must be established to support these methods. Three new roles are suggested:

- Maintenance and support of methods. Due to circumstantial changes and improved knowledge methods will always need maintenance. Maintenance responsibility adds a new role to the organization.
- Gathering and processing of basic data for decision tools. The large amount of information needed often makes it difficult to apply structural methods. The attention is focused on the method and the resources requirement for handling of data tend to be overlooked. This work should be performed by a central function since much of the data is common for several systems.
- Expert support. Experts already exist at R&D but the expert role has to be well defined. The experts should be trained in a number of the structured methods given in Chapter 4. Further it must be clear where experts are located in the organization.

The formal role description of senior engineers in theory provides us with exactly what is needed, but obviously it does not work in practice. The main explanations are that the persons do not have time and that the role is unclear for others. The technical career therefore needs to gain more acceptance and measures are needed to improve its attractiveness, but also to clarify the role of an expert. Today there are only a few positions as technical manager covering the large developing organization working with system development.

In Figure 8 the results from the survey has been compared to the similar surveys mentioned above [9][20][2]. The Finnish survey had evaluation matrix and rating defined as two different methods, in the comparison they are summarized to one, "Evaluation matrix, Rating". The methods have otherwise been matched exactly when data was available and set to zero if not. The comparison shows one possible explanation why developers would like to increase the use of concept review meeting and checklist, the use of those methods is extremely low in comparison.

Decision making by review meetings is supported by Christensen and Krainer [4]. They suggest that the project review meeting should be used as decision point in projects with high degree of uncertainty.
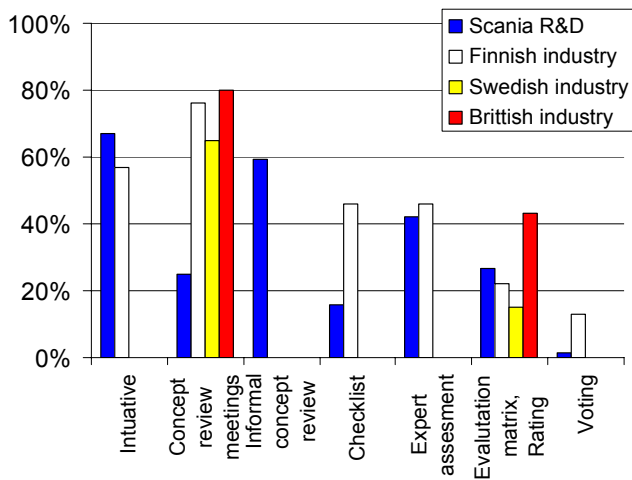
Figure 8 Utilization of methods in system design

5.2.5 DECISION

A decision is the agreement to adopt a certain alternative to resolve the issue [23]. In general there is no established process for decision making. Most information about decision making was received from respondents within engine system development. The recently adopted RUP-process is considered as effective and decisions made within the change control board are regarded as well founded. Issues, in the event management system are prepared prior to the meeting and argued by the issuer at the CCB. More complex issues are argued by the most experienced participants at the meeting. Further, decisions made at the CCB are given the support of the management group which is present at the meeting.

- A change control board should be established for chassis, power train and cab according to RUP. The representative at the system integration meeting will report the decisions made at the local meeting and present new issues that need to be considered.
- A system architect must be appointed and given the task of representing the system at the system integration meeting.

The successful use of the event management system in the CCBs leads to well founded decisions. It is reasonable to assume that this process could be used successfully within several development teams. The use of one common process will integrate the overall development process and eventually solve the problem of the "global CAN-village" within system development.

The importance of clearly documenting each decision must be emphasized. It should be documented how the decision was made and amongst which different alternatives the choice was made. The transfer of knowledge depends on this documentation and is crucial for the next development team entering into a related issue [4].

To ensure the confidence in the "system integration meeting" each part of the organization must be represented and the task must therefore be prioritized.

6 CONCLUSIONS

The quality of the developed systems is used by the company as a sales argument and the product as whole is considered to be state of the art. The reasons for this success found within this work are well motivated engineers working in an open minded climate. Some locally adopted solutions were found to have very high potential and should be further used.

- The use of Change Control Boards provides a structured way of handling tasks.
- The system architect role manages and coordinates design changes
- Formulating and using basic design principles that tie the project together.
- Evaluating different alternatives using trade-off curves

The main problem found was to be the general confusion about where decisions are made. This problem is connected to the finding that the level of the electrical issues discussed at the project monthly meeting is not harmonized. New employees where found to feel a lack of expert support and the use of structured methods were found to be very low.

We suggest and prioritize three improvements to respond on those problems which are further explained in the following sections.

1. Strengthen the role of the technical career
2. Improve knowledge transfer trough documenting design know-how
3. Educate engineers in the use of structured methods

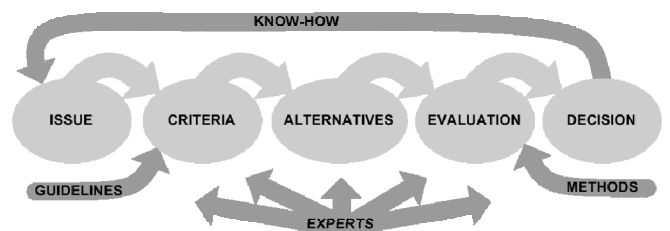These improvements are illustrated in Figure 9.

Figure 9 Proposed improvements related to the IBIS model [23]

6.1 IMPROVEMENT OF THE TECHNICAL CAREER

The low number of formally appointed experts makes the role invisible and is also very low compared to other more traditional parts of the organization. Two or three new technical managers should be appointed within system developing organizations. Possible technical areas to be covered are application software, operating system and human machine interface.

Each newly employed engineer should be given a suitable senior engineer as coach during there first year. The senior engineer does not need to be within the same organization, but should be an expert within the same field. The first meeting should take place 2-3 months after the employment starts and the second and third at 4-5 months interval. Topics to be discussed should be methods, technology and personal network. To ensure that meetings are made this should be made a mandatory part of the introduction for newly employed.

To further enhance knowledge transfer, senior engineer should be made available for support in methods and technology for all developers. Time for knowledge transfer must therefore be allocated to the senior engineer. This measure will clarify the role of a senior engineer and enable knowledge transfer.

6.2 DESIGN KNOW-HOW THROUGH CHECKLISTS AND GUIDELINES

Well written guidelines are available for electrical and electronic system development, but this work must be updated and more widely promoted. Guidelines are available for electrical and electronic system development, but this work must be updated and more widely promoted. Guidelines solve the earlier stated problem with insufficient requirement specifications by supporting the engineer.

Checklists should be developed to aid the developer in each design step and thereby ensure product quality. There is a checklist available for mechanical design, but this must be made suitable for system development. The document describing the development process in the powertrain department could be used as a starting point. An updated checklist would make the project decisions harmonized by clarifying when decisions need to be made at what level.

Design know-how is currently not well documented within system development, but a method and template is developed and in use in other areas. Design know-how for system development should be documented using this template.

6.3 EDUCATE ENGINEERS IN THE USE OF STRUCTURED METHODS

Structured methods make the decision process visible and ensure that it can be repeated. The cost of pursuing the wrong alternative is avoided and recently employed engineers can carry out an evaluation of alternative concepts.

The survey shows that the use of unstructured methods such as an intuitive choice is high, but the use of structured methods mentioned in the related work section is very low. The knowledge and use of structured decision methods should be increased by adding this topic to the introductory ECU-system course. This is important for the recently employed.

ACKNOWLEDGMENTS

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