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Key Challenges in Decision Making for Automotive E/E Architectures

Peter Wallin

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School of Innovation, Design and Engineering
Mälardalen University
Västerås, Sweden

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Abstract

The amount of electronics in vehicles is growing quickly, thus systems are becoming increasingly complex making the engineering of these software intensive systems more and more difficult. In particular, an architecture supporting the business goals is a prerequisite for successful design.

In this thesis two case studies have been made including three automotive companies with purpose to investigate the key issues related to real-world decisions when developing Electrical and Electronic (E/E) system architectures in the automotive industry.

The results show that many of the identified issues relate to non technical areas such as organization, process, methods and tools, and management. Examples of identified issues are the deficient understanding of the electrical system and software at management level, and the lack of a specific process for architecture development. To cope with these issues we suggest the following actions: Educate management, increase the use of structured decision making, improve the architecture development process, clarify responsibilities in the organization and clarify development strategies.

As a possible solution to one of the suggested actions we have developed a method to evaluate how new functionality is successfully integrated into an existing architecture. The method is a combination of the Architecture Tradeoff Analysis Method, ATAM, and the Analytical Hierarchy Process, AHP. The method firstly supports a structured way of listing system goals, and secondly, it also supports the making of design decisions.

Swedish Summary - Svensk Sammanfattning

Det är drygt 30 år sedan mjukvara började användas i bilar. Mjukvara användes då för att kontrollera tändningen och systemet var helt fristående. I en modern bil idag finns det miljontals rader programvarukod och flera kilometer med kablage som kopplar samman de upp till 70 datorerna som kan finnas tillgängliga. Allt detta gör att de mjukvaruintensiva systemen blir mer och mer komplexa och svåra att utveckla.

Anledningen till den stora mängden elektronik och mjukvara är framförallt tillväxten av nya avancerade funktioner för: ökad säkerhet, mindre avgasutsläpp och ökad komfort. Exempel på sådana funktioner är adaptiv farthållare (farthållare som anpassar avståndet till framförvarande bil), automatisk inbromsning och kollisionsvarnare. Även relativt små och enkla system kräver mer minne och större kraftfullare processorer. Idag krävs det till exempel tre gånger mer minneskapacitet i skakskyddet till cd-spelaren, än vad som tog Apollo 11 fram och tillbaka till månen år 1969.

Elektroniksystemet i ett fordon delas ofta mellan flera modeller och varianter. Det gör att systemet måste kunna anpassas för att användas både i en billigare bil med endast enklare basfunktioner, och i en bil som är full med avancerade funktioner. Samtidigt är det svårt att värdera hur mycket som ska delas då det kan betyda att den billigare bilen får onödiga kostnader i form av mer avancerade komponenter än vad som krävs för basfunktionaliteten.

I den här uppsatsen presenteras nyckelfaktorer som speglar vilka problem som finns under utvecklingen av elektroniksystem idag hos tre internationella fordonstillverkare, som har huvuddelen av sin verksamhet i Sverige. Nyckelfaktorerna har identifierats via ett 30-tal intervjuer. Många av dessa problem går att härleda till icke tekniska faktorer såsom organisation och ledarskap.

Ett problem som diskuteras i avhandlingen är den bristande förståelsen för elektronik och mjukvara på chefs- och ledningsnivå. Avsaknaden av tydliga processer för utveckling av elektroniksystem är ett annat. Baserat på de problem som identifierats föreslås en rad åtgärdspunkter: utbilda chefer, utöka användandet av strukturerade beslutsmetoder, förbättra utvecklingsprocessen för elektroniksystem, tydliggöra ansvarsfördelningen i organisationen och tydliggöra utvecklingsstrategierna.

Som lösning på ett av de identifierade problemen har vi tagit fram en metod för att utvärdera hur nya funktioner kan integreras i ett redan existerande elektroniksystem. Metoden tillhandahåller ett strukturerat och effektivt sätt att resonera kring betydelsen av olika systemegenskaper, såsom flexibilitet, säkerhet, pålitlighet och servicebarhet.

To My Lovely Wife

Acknowledgement

First of all I would like to thank my supervisor Prof. Jakob Axelsson, for always finding time to guide me, both in the world of research and in the automotive industry. I would like to thank my assistant supervisors Prof. Christer Norström and Dr. Stig Larsson for all the invaluable input to my research.

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During this time I have made quite a few trips to Gothenburg and I would like to acknowledge Ana Magazinovic at Chalmers for helping me with interviews, and reviews of papers; together with Fredrik Pettersson they have guided me to different cultural events (pubs) in Gothenburg.

I would like to acknowledge the architecture group at Volvo Car Corporation, in particular Helen Svensson for letting me participate in one of their projects and introducing me to the everyday challenges in the automotive industry.

Many thanks to my friends at the department, Fredrik Wallin (not really at the same department, but close enough), Stefan Johnsson and Andreas Hjertström, for all the discussions, both work related, and more important what technical gadget that is next in line to be bought.

Joakim Fröberg has been a great co-author and provided very useful input to the thesis, thank you. At the department there are many people that made my time both pleasant and fun, thank you Jörgen Lidholm, Monica Wasell, Håkan Gustavsson, Markus Lindgren, Hüseyin Aysan, Ewa Hansen, Jonas Neander, Rikard Land, and all the ones I have forgotten.

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Finally, many thanks to my wife, Katarina, for always supporting me, encouraging me, and making every day joyful and worth living. I love you!

Peter Wallin

Västerås, September 16, 2008

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List of Publications

Publications Included in the Licentiate Thesis

Paper A: Peter Wallin and Jakob Axelsson. A Case Study of Issues Related to Automotive E/E System Architecture Development. In *Proceedings of the 15th IEEE International Conference on Engineering of Computer-Based Systems*, Belfast, Northern Ireland, March 2008.

I was the main author of this paper and had help from Ana Magazinovic from Chalmers in collecting data, and from my supervisor Jakob Axelsson in the analysis part. Jakob also wrote most of the validity section of the article.

Paper B: Peter Wallin, Stefan Johnsson and Jakob Axelsson. Issues Related to Development of E/E Product Line Architectures in Heavy Vehicles. To appear in *Proceedings of the 42nd Hawaiian International Conference on Systems and Science*, Honolulu, Hawaii, January 2009.

In this paper I was the main author and had help from Stefan Johnsson during the collecting of data and during the analysis of data. Jakob Axelsson helped analyzing the data and also wrote major parts of the validity section.

Paper C: Peter Wallin, Joakim Fröberg and Jakob Axelsson. Making Decisions in Integration of Automotive Software and Electronics: A Method Based on ATAM and AHP. In *Proceedings of the 4th International ICSE workshop on Software Engineering for Automotive Systems*, Minneapolis, USA, May 2007.

I was the main author and the paper was done in close collaboration with Joakim Fröberg, who provided most of the ideas and thoughts on

ATAM. I provided the thoughts around AHP and how they could be used together. The writing was divided equally between the two of us.

Other Publications by the Author

- Joakim Fröberg, Peter Wallin and Jakob Axelsson. Towards Quality Assessment in Integration of Automotive Software and Electronics. In *Proceedings of the 6th Conference on Software Engineering and Practice in Sweden*, Umeå, Sweden, October 2006. (Early version of Paper C.)
- Stig Larsson, Anders Wall and Peter Wallin. Assessing the Influence on Processes when Evolving the Software Architecture. *9th International Workshop On Principles of Software Evolution*, ACM, Cavtat, Croatia, September, 2007.
- Peter Wallin, Joakim Fröberg and Jakob Axelsson. Making Decisions in Integration of Automotive Software and Electronics: A Method Based on ATAM and AHP. *Real-Time in Sweden (RTiS)*, Västerås, Sweden, August 2007. (Same as Paper C.)
- Stefan Johnsson, Peter Wallin and Joakim Eriksson. What is Performance in Complex Product Development? *R&D Management 2008*, Ottawa, Canada, June 2008.

I

Thesis

Chapter 1

Introduction

It has been 30 years since the first piece of software was used in a vehicle [1]. That particular software was used to control the ignition of the engine. The first software systems in vehicles were local and did not have any communication between different systems. Since then a lot has happened and today almost all new functionality involves advanced control of electronics and software.

The automotive industry is traditionally a mechanical industry. Of course mechanics is still the foundation of the vehicle but the amount of software and electronics is increasing rapidly. According to [2], 23% of the overall cost of high-end cars today is related to the Electrical/Electronic (E/E) system, and this figure is believed to increase to 35% in 2010 [3]. Today up to 90% of all new innovations in a car are realized with electronics and software [4].

One of the reasons for the large increase of software and electronics are the customer demands for new safety and convenience functions such as adaptive cruise control, blind spot detection, forward collision avoidance, lane departure warning and many more. Further, to cope with new regulations on emissions the use of software and electronics is a necessity. For the Original Equipment Manufacturer (OEM) software and electronics aids in test procedures since many tests can be automated. It further provides the OEM with flexibility in managing variants by parameterize the software differently instead of using different mechanical components. An example of this is the software controlling the engine that can be parameterized differently to utilize different engine models.

Some parameters that make it hard to develop the E/E system are the assumed long operational life time and a complex supplier structure. At the same time much of the functions controlled by electronics are safety critical and periodic maintenance cannot be assumed. Furthermore, the complexity is increased due to the different variants with many different configurations. The reason for this is partly due to different customer demands but also due to the legal requirements of each country where the product is sold. To handle the different variants most automotive companies use a product line approach and many models share a common platform.

The E/E system architecture affects the qualities of the system and thus is an enabler to become successful in developing E/E systems, but the importance of the architecture is often neglected. This is mostly due to the fact that it is hard to see any direct customer value provided by the architecture. However, if unsuccessful in the architectural work, adding new functionality could be costly, the wanted quality could not be achieved, or it could even be impossible to include the new functionality at all. This thesis describes key challenges in decision making for automotive E/E architectures and how to cope with these challenges in a satisfying way.

1.1 Outline of Thesis

In Chapter 2 we discuss the term architecture and how it is used in an automotive context. Research scope and motivation of the work leading up to the research questions is discussed in Chapter 3. We also present related work and the methodology used to answer the research questions. In Chapter 4 we present the companies involved in the research. Continuing with Chapter 5 we revisit the research questions and summarize the contribution of the thesis. In Chapter 6 we conclude the first part of the thesis with a discussion and give some indications about where future research will be made. In the second part of the thesis, all included papers are presented.

Chapter 2

Automotive Architectures

In this chapter automotive E/E system development is introduced. The chapter also defines the meaning of an architecture and different aspects of architectural development.

2.1 Automotive E/E System Architecture

The term architecture and system are frequently used when developing automotive electrical and electronic systems. However there is not always a common understanding of what is included in an architecture. During interviews with employees at different automotive manufacturers we asked for their view of what an architecture is. The placement of physical components and software was one respondent's idea of an architecture. Another said it is only the cabling, harnesses, and power consumption that are part of the architecture. One respondent claimed that an architecture is the guiding rules for how to build a system and also the composition of elements and their relationship.

The views on what an architecture is differed although a few respondents mentioned the IEEE definition of architecture: "The fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution" [5]. This definition is quite general and most of the respondents, own ideas on what an architecture is can be included in this definition.

The E/E architecture in vehicles includes sensors, actuators, and control units as well as other hardware components. The architecture does not specify the details about each sensor, but more that there should be a sensor measuring the distance to objects in front of the vehicle i.e. if it is a radar, high speed camera or a laser range finder is not part of the architecture.

Further the physical network, software and wiring is part of the E/E architecture. A reason for this is the tight coupling between hardware and software. For instance, a braking application is very tightly bound to the hardware for which it is tested and developed. A change of actuators or other hardware components in such an application would likely generate a change of software functionality.

According to the IEEE definition the architecture also includes guiding principles and rules about the design of the system such as type of communication protocols. It should also include guidelines about how the system should evolve.

2.2 Different Architectural Views

An automotive electronic system architecture can be described in many ways using different views as stipulated in [5].

Physical View

A commonly used view is the *physical view* showing where the different Electronic Control Units, ECUs, are physically placed and also shows how they are connected to each other via different networks; CAN [6], Flexray [7], MOST [8] etc. An example of this view is shown in Figure 2.1.

Logical View

Another view that is important is the *logical view*. It describes logical relationships and how different components depend on each other logically. The logical view is independent of the physical view. However there might be physical limitations that will favor a different logical solution.

Electrical View

A view that is more unique for an automotive E/E architecture compared to a general software architecture is the *electrical view*. This view shows the electrical distribution in form of cabling, fuses and power generation, and storage.

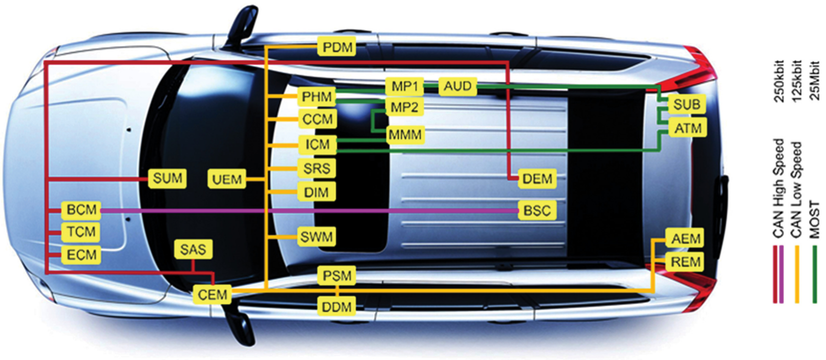

Figure 2.1: Physical view of the Volvo XC90.

In the automotive industry the physical and electrical views are usually the one that will get most attention. This is mainly due to the fact that it is easier to understand placement of real physical components instead of the sometimes more abstract logical view.

In a vehicle the physical and electrical view is important since many constraints are determined by these views, for example the space in a vehicle is fairly limited, packaging is always a problem, but not having a good logical architecture might increase dependencies between different ECUs. An increased number of dependencies will most likely cause the system to be more complex, harder to remove or change components, and more difficult to add new functionality.

Another reason why the physical and electrical views gets most attention is that many processes are dependent on these views, such as manufacturing and service.

2.3 Architecture Process

The process of designing an architecture for an automotive system is complex. The architecture should comply with many different stakeholder needs. A general process for architecture development is described in [9] including seven key activities. One of the more important steps in the process is to identify and engage stakeholders. A problem is that many stakeholders do not see the architecture as their core business and easily prioritize other activities.

Another problem is that the requirements for the functionality that the architecture should support are finalized at a later stage. This means that the team responsible for the architecture has to make qualified guesses about what the future requirements might be and what functions that should be supported.

2.4 Development Context

In the automotive industry many vehicle models share the same platform and architecture. The architecture has to comply with requirements, not only from different models within one brand, but also requirements from different brands. For example a high-end Volvo car might share architecture with a low-end Ford car. This means that the architecture has to be scalable to support both, and not making the architecture for the Ford model more expensive while at the same time still support the larger amount of functionality required by Volvo.

There are many parameters to consider if it is beneficial to share an architecture between models or not. One reason for sharing architecture could be that the quality is increased when reducing the number of architectures since more development time can be used for each architecture. On the other hand if the architecture becomes more complex when enabling support for different models the quality might go down. If the architecture is tailor suited for a particular model the development cost for that particular architecture will most likely be lower, but if considering that sharing the architecture means that development cost will be shared between many models it will probably generate a better business case for the company as a whole. Further, the production cost can be lower when sharing the architecture since larger quantities of the same component can be purchased.

Common for all automotive developers is that they purchase subsystems from different suppliers and integrate these systems. Much of the software is not made in-house and is usually included in the specific hardware. If one for example buy a braking system both software and hardware are bought from the same supplier. Although the AUTOSAR[1] initiative [10] might enable that software and hardware are purchased from different suppliers or that the software is developed in-house. Automotive development is also characterized by relatively long lead time where the start of production is around four years after start of development.

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[1] AUTOSAR (AUTomotive Open System ARchitecture) is an open and standardized automotive software architecture, jointly developed by automobile manufacturers, suppliers and tool developers.

Suppliers in the automotive domain are usually very large. This makes some of the Original Equipment Manufacturers, OEMs, relatively small compared to some suppliers. The supplier tends to strive for using a design developed for some other OEM when offering to sell a component. The OEM on the other hand usually prefers to get the function developed exactly according to its own defined requirements. By choosing something already developed for another OEM the cost might be reduced and also the quality increased.

Chapter 3

Research Scope

In this chapter we present a motivation of the work leading up to the research questions. We also discuss the methodology used to address each research question. In the last section of the chapter related work is discussed.

3.1 Motivation and Positioning of the Work

With the increasing amount of software and electronics, decisions made during E/E system development become more and more important. Today an incorrect decision in the architecture can severely increase the cost, both during development and also in later phases such as for example maintenance. However, little research has been done about how such decisions are made today.

The architecture itself does not provide any customer functionality, instead the design of the architecture affects different qualities such as flexibility, dependability, serviceability, security and maintainability. These quality attributes are hard to value, both against each other and against cost. The benefit for enhancing serviceability might not be seen until later in the life cycle of the vehicle and it is extremely hard to value such attributes. Furthermore, even if a certain quality attribute is valued it is difficult to know what particular design decisions that enhance the wanted quality.

When designing an architecture the influence from different areas is an aspect that is important to consider. For example the structure of the organization might put constraints on the architecture. Other areas that affect the architecture are management and business, and processes methods and tools

(PMT[1]). These non technical factors have a large impact on the architecture and therefore we believe they are important to consider. Figure 3.1 shows how the architecture relates to other areas that are affected.

It is the architecture part in Figure 3.1 we focus on in this research, and how it is affected by the other areas.

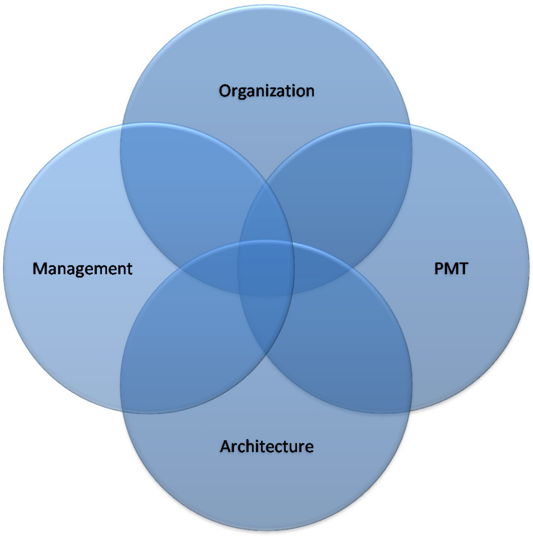

Figure 3.1: Positioning the work.

3.2 Research Question

Our research aims at surveying methods and processes used in the automotive industry today to make decisions regarding the E/E system. Another aspect is to investigate which the key factors affecting a decision are. The reason to start with exploring which key factors are important today is to get a broad understanding of the issues related to automotive E/E system development. This is beneficial for the companies studied to better understand the issues that exist. Without this broad understanding of what the real issues are it is hard to provide new methods and tools that are really useful.

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[1] PMT is a general expression used in the automotive industry, therefore we have chosen that acronym despite the fact that it might not be well known in academia or other industries.

Below are the research questions that the licentiate thesis addresses. RQ1 is discussed in Paper A and B. Paper A concerns the development of a car's E/E system architecture. In Paper B we identify issues related to the development of E/E system architectures from the viewpoint of heavy vehicles. RQ2 is discussed in Paper C.

RQ1: ***What are the key issues affecting real-world decisions regarding a vehicle's electrical and electronic system architecture?***

RQ2: ***How to make effective decisions when adding new functionality to an existing electrical/electronic system architecture?***

Naturally, the answer to these research questions must be sought at the companies carrying out development of electronic architectures. Further, it cannot be assumed that only technical issues are related to these questions, but also organization and management, as well as processes, methods, and tools must be considered. Therefore, a collaborative project was set up with leading automotive industries in Sweden. This collaboration is further described in Chapter 4.

One major difference between the car industry and the heavy vehicle industry is their customers. A car is in most cases a consumer product while most heavy vehicles are sold business to business. Thus, the reason for buying a heavy vehicle or a car differs quite a lot. As some people argue, "a car is bought with the heart and a heavy vehicle is bought with a spreadsheet". Also the amount of electronics and software is larger in a car due to customer demands for infotainment and active safety.

The benefit of being able to compare the results from the two case studies gives us the ability to generalize results much more then what would have been possible if only considering one domain. In Chapter 5 we provide a short discussion about the differences and similarities between the different companies participating in the research.

3.3 Methodology

To answer the research questions stated above we used two different methods.

3.3.1 Method for RQ1: Case Study

In the first two papers answering the first research question we made two different case studies. In paper A we used an exploratory single case study and in paper B we used an exploratory multiple case study. Exploratory studies reveal answers to questions based on what, how, and why.

We choose the case study methodology since we wish to explore what people working in the organization think are the most challenging issues within the development of E/E systems. As our tool to collect data we used semi-structured interviews since it provides us with the flexibility to change direction based on the answers we get. Semi-structured interviews have predetermined questions, but the order can vary based on the interviewer's perception of what seems most appropriate [11]. Additional questions can also be constructed during the interview and it is also possible to remove questions that seem inappropriate.

Another important advantage of using interviews instead of for example surveys is the ability to explain a question further if the respondent is unsure about how to interpret the question. More information about different methodologies can be found in [11], [12] and [13].

Below are the different steps in the case study. Each step is further described in Paper A and B. In these papers there is also an in depth discussion about validity.

Planning and Preparation

To select suitable respondents we used a contact within the organization to select respondents. Most of the respondents contacted were also able to participate in the study. The same set of questions was used for both case studies. To test that the questions were suitable we made a pilot interview and analyzed it separately. Minor modifications in the questions were made after the pilot.

Interviews

All interviews lasted between 50 and 120 minutes. At each interview two researchers participated, one asking questions and the other taking notes. We did not use any recording devices due to the risk of limiting the openness of the respondent. Instead all interviews were transcribed directly afterwards to avoid any misinterpretations of the notes.

Analysis

In the next step we analyzed the result from the interviews. This part was done by extracting statements from each interview and putting them in a database. All statements were printed and similar statements were grouped together. The grouped statements were rewritten and combined to a more general form to depersonalize all data. For a statement to be considered as an issue at least two respondents independent of each other had to name that statement.

Validation

To validate that the issues found were relevant we sent a survey to all people that participated in the interviews. Each respondent marked in a questionnaire how well they thought each issue complied with their own opinion.

3.3.2 Method for RQ2

In Paper C we propose a method that can aid when choosing between different integration strategies. The method should be used when adding new functionality to an existing system. The method in this paper was mostly based on literature reviews and discussions with experts. By combining and modifying two methods, the Architecture Tradeoff Analysis Method (ATAM) [14] and the Analytical Hierarchy Process (AHP) [15], we got a method that can firstly elicit important qualities of the envisioned system, and secondly a method that aids in choosing a particular integration strategy.

3.4 Related Work

In this section we discuss work that is related to the thesis. A short section presents the current challenges in automotive software engineering and what the incentives are. We also discuss some models and evaluation methods that are relevant. Further related work is provided in each of the papers included in the thesis.

3.4.1 Challenges

Challenges in automotive software engineering are discussed by Broy in [16]. According to Broy one of the issues in the automotive industry today is the lack of competence in software engineering. A further challenge is that the current development processes for software are insufficient. Therefore there is a need for new processes that can aid in reducing the complexity, and at the same time enables innovation and save cost.

In [17] Grimm claims that a prerequisite for an OEM to be successful is to have competencies in software development processes and software quality management.

Pretschner et al. have in [18] listed five areas that are salient for automotive software development. One of them is the focus on unit cost of electronic components. Since vehicle components are mass produced under approximately 7 years, a € 1 cost reduction for one component will lead to a substantial overall cost reduction. This makes engineers focus on reducing the needed computational power and memory by optimizing the code for that particular processor and not including more memory than the minimum needed. The major drawbacks with this approach are that it will be hard to add new functionality or change processor without rewriting the software.

In our case studies we have seen similar challenges as the ones described above. However these authors discuss the challenges from a software perspective while in our case study we have taken a broader approach, focusing on the E/E system architecture.

3.4.2 Organization

Some of the issues from the the case studies (presented in Chapter 5) relate to the organization. The reason why the organizational aspects are important can be described with Conway's law [19] from 1968 that says: "Any organization which designs a system will inevitably produce a design whose structure is a copy of the organization's communication structure".

The lack of not being able to cooperate between different departments will affect the productivity negatively as discussed in [20]. Based on interviews with managers from an engineering consultancy firm they conclude that ineffective interaction between departments is costly both for the organization and their people.

In [21] they list ten principles of collaborative organizations. One of the principles is to align authority, information and decision making. If failed to do so, the decisions that are made will easily be overturned with few attempts to explain the reason to those who made the original decision. This is closely related to one of the issues described in Chapter 5 stating that *decisions are usually poorly motivated and it is hard to reach consensus and acceptance in a decision*.

3.4.3 Management

Management influences the architecture, and often the lack of understanding for software and electronics affects the architecture negatively. This is an issue that is supported by [22] stating that systems engineering is mostly driven from a mechanical and electronic point of view and seldom from a software perspective.

Related to why management seems to have a lack of understanding for software and electronics could be the extra layer of complexity, causing the systems to be too complex to overview effectively. In [23] it is shown that the learning cycle of manager's breaks down in complex environments. A reason for this is the time lag between cause and effect.

A management related issue discussed in Chapter 5 is to utilize enough resources in advanced engineering projects. One reason that a company fails to do so might be that old development projects cannot keep their deadlines and are therefore utilizing resources that were allocated for advanced engineering projects. This issues with a possible solution is discussed in [24].

3.4.4 Evaluating an Architecture

In the automotive industry with many models sharing the same architecture, scalability is an important quality. One of the issues found in the interview study confirms this. A possible solution to this issue could be to use the approach suggested in [25] where real options are used to value scalability. A problem that can arise when an architecture and functions are shared between brands is discussed in [26].

Another issue found in the case study relates to the lack of method to evaluate the business value of different architectural design alternatives. This issue is supported by Bosch in [27]. As a possible solution to this issue an iterative, scenario based evaluation of a software architecture is proposed in [28]. Another scenario based approach is the Architecture Tradeoff Analysis Method (ATAM) [14] where quality attributes are used to evaluate a software architecture.

In [29] a method for evaluating automotive E/E system is presented. It suggest a system level architecture design methodology supported by tools and methods for quantitative evaluation of key metrics of interest, related to timing, dependability and cost. To generate an optimized E/E system level design a tool chain supporting AUTOSAR [10] is suggested in [30]. It is possible that these methods can be used to successfully evaluate an automotive E/E architecture.

Related to automotive E/E architectures [31] suggests an approach on how to balance between a centralized architecture and a fully distributed architecture, with the concept of platform-based design [32] and the Metropolis framework described in [33] and [34]. Different architectures are valued based on four different qualities: control latency, geometric metrics (number of connectors, wire length), serial data metrics and flexibility.

Many of these methods seem promising and can probably provide partial solutions to the issues found for RQ1, but have to our knowledge not gained any success in real cases in the automotive industry.

Chapter 4

Project Set-up

This research has been done in close collaboration with industry, mainly three different automotive companies. The reason for choosing these particular companies as collaborators is that they are internationally recognized companies, all very competitive within their domain. Another reason is the previous good relations between our university and these companies. In this type of research this is important since trust and credibility are crucial in order to get sincere answers in case studies and also to get the cooperation needed to be able to perform an interview study at all. In the following sections of this chapter, these companies are described as they were at the time when the research was carried out.

4.1 Volvo Car Corporation

Volvo Car Corporation (VCC) has its headquarters, including product development and many other functions, in Gothenburg, Sweden. The company is a producer of premium cars, with special focus on safety, environment, and quality. It has approximately 25,000 employees and manufacture and sell close to 500,000 vehicles each year worldwide. It is a subsidiary of the Ford Motor Company (FMC) since 1999, and has close co-operation primarily with Ford of Europe in Germany and Jaguar-Land Rover in the UK. For these brands, VCC has a leading responsibility for the E/E architecture.

4.2 Volvo Construction Equipment

Volvo Construction Equipment (VCE) is a division within the Volvo Group that develops and manufactures construction equipment such as, wheel loaders, excavators, articulated haulers, and graders. Responsible for the E/E system development is the component division of VCE. In total at VCE around 16,000 people are employed and approximately 140 are directly involved with E/E system development.

4.3 Volvo 3P

Volvo 3P (V3P) is a division within the Volvo Group responsible for product planning, product development, purchasing, and product range management for the three truck brands that are owned by the Volvo Group (Mack Trucks, Renault Trucks and Volvo Trucks). The development is focused to Gothenburg, Sweden but some activities are done in the United States and France. In total there are around 3,000 employees at V3P and the sales volume is approximately 220,000 trucks per year. The E/E department has roughly 600 employees.

Although both VCE and V3P are part of the Volvo Group they have limited cooperation and have their own business strategies. Further VCE has different legal requirements than V3P since VCE is to 90 % a manufacturer of off-road machinery. Furthermore VCE has more product variants and at the same time lower sales volumes than V3P. The architecture is part of a platform that facilitates variability options supporting different brands and products.

4.4 Development Processes

All three companies have a similar development process. The development process is based on a general stage gate model described by Cooper [35]. The basic steps of the process used by the Volvo Group are described in Figure 4.1. Volvo Cars has a similar development process that is a joint process with Ford Motor Company. Most work related to the architecture is done in the pre-study phase and in the concept study phase. Below is a short summary of the key activities in each step of the development process used by the Volvo Group.

Pre-study phase. Define the scope of the project by balancing project targets, developing requirements and alternative solution concepts.

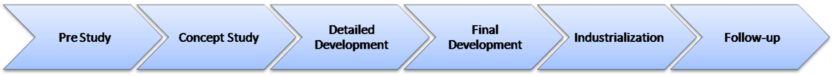

Figure 4.1: Overview of development process used at V3P and VCE.

Concept study phase. Analyze alternative concepts and select one for development. Document and sign off the preliminary Project content.

Detailed development phase. Define and approve the solutions to be implemented and the project's delivery commitments from all areas. Freeze and sign off the Project content.

Final development phase. Build, verify, validate and refine the product solution. Refine market, aftermarket, manufacturing, and assembly solutions.

Industrialization and commercialization phase. Install, prepare and verify the industrial system. Launch product and aftermarket products. Finalize product verification and validation to approve product release.

Follow-up phase. Hand over product to line organization, follow up project target fulfillment, summarize project experiences and close project.

Chapter 5

Summary of Results and Contributions

The contribution of the licentiate thesis is an indication of what the key factors are when making automotive E/E system design decisions. In the first out of two case studies, Volvo Cars (VCC) was the studied object and in the second case study two divisions, Volvo 3P (V3P) and Volvo CE (VCE), within the Volvo Group were the research objects. In the second case study we treated the two divisions as two separate organizations and analyzed each division separately before comparing them.

The two case studies indicate that non-technical parameters are as important as technical parameters in the decision making process. Furthermore, the thesis presents how different automotive companies with different types of products deal with the problem of making decisions when designing automotive E/E systems. Many of the identified issues are common for all three organizations although there is a difference in type of product, volumes, and number of variants.

As a further contribution of the two case studies we provide some suggestions for actions to cope with the identified issues. We propose the following actions; Educate management, increase the use of structured decision making, improve the architecture development process, clarify responsibilities in the organization and clarify development strategies.

The final contribution of the thesis is a method for making structured and effective decisions when designing automotive E/E systems. This is a possible solution to one of the issues identified in the two case studies.

In Chapter 3 we discussed the research questions we aim to answer in this thesis, and below we revisit these questions and describe our findings. The results presented here is a further synthesis of the results presented in each paper.

5.1 Key Issues Affecting Architectural Decisions

In this section we present the results from our findings related to the first research question. The question we posed was

RQ1: What are the key issues affecting real-world decisions regarding a vehicles electrical and electronic system architecture?

To answer this question we made two separate interview studies, one exploratory single case study and one exploratory multiple case study, each study is further described in Paper A and B respectively. The unit of analysis was the E/E department at VCC, V3P and VCE.

The findings were validated with a survey, and in section 5.1.3 that result is used to compare the different companies.

The study involved 27 respondents, all with extensive knowledge and experience from developing automotive E/E systems. Respondents included for example a project manager, a technical leader, a senior technical advisor, a system architect, a software architect, a senior manager, and a technical expert. In total we found 21 issues affecting real-world decisions regarding a vehicle's E/E system architecture.

These issues were categorized into the four areas introduced in Chapter 3, *architecture*, *organization*, *management and business*, and *process, methods and tools (PMT)*. All issues were extracted from interview data, and the classification made by two researchers. Many of the issues relate to more than one of these areas. Below we have made a distinction between cross-cutting issues, i.e. issues that are related to more than one area, and non cross-cutting issues, i.e. issues that only have a relation to one area. An interesting finding is that all issues mapped to the architecture are cross cutting. The reason for this could be that if a problem occurs that is only related to the architecture it is solved directly.

Below we discuss a selection of these issues and what the problems of each issue might be and how they can be resolved. A full list of issues with mapping to the different areas are shown in Table 5.1.

Table 5.1: Mapping of issues to high level attributes.

Issue	**Architecture**	**Organization**	**Process, Methods& Tools**	**Management & Business**
1. Several brands and products share the same architecture but have different priority order between, for example, quality and cost	**X**			**X**
2. There is a lack of clear strategy for what development should be done in-house and what should be done at external suppliers		**X**		**X**
3. Architectural issues should be handled more energetically and it should be made clearer who in the organization is responsible for such issues	**X**	**X**		**X**
4. There is a lack of process for architecture development	**X**		**X**	
5. There is a lack of clear long-term architectural strategy	**X**			**X**
6. There is a lack of understanding of the electrical system and software at the management level				**X**
7. There is no clear process for handling requirements			**X**	
8. The cooperation between product development and product planning needs to be improved		**X**		**X**
9. There is no method or model for measuring and follow up of quality problems during development			**X**	
10. There is a lack of method or model to evaluate the business value when choosing the architecture	**X**		**X**	
11. It is unclear how to prioritize between time, cost and quality				**X**

Table 5.1: Mapping of issues to high level attributes.

Issue	**Architecture**	**Organization**	**Process, Methods& Tools**	**Management & Business**
12. The complexity in the organization as well as the product has increased which has led to a situation where the existing processes are insufficient		**X**	**X**	
13. Decisions are usually poorly motivated and it is hard to reach consensus and acceptance in a decision		**X**	**X**	**X**
14. Architecture decisions are often made based on experience and gut feeling	**X**		**X**	
15. History has a large influence on architectural decisions, and is reflected both in choice of technology and in the organization	**X**	**X**	**X**	
16. The modeling tools used today demand resources and provide little value			**X**	**X**
17. Decisions are easily made that suit one's own project, team or component even though it leads to a poorer overall solution		**X**		**X**
18. Technical parameters are regarded as less important than cost when selecting components or suppliers			**X**	
19. Advanced engineering projects have low priority and to increase the priority they are merged into development projects too early				**X**
20. Processes and methods are less valued than knowledge and competence of individuals			**X**	**X**
21. Prestige and rivalry complicates cooperation between different departments and business units		**X**		**X**

5.1.1 Non Cross Cutting Issues

The issues that are isolated to one area can hopefully be resolved more easily than the cross-cutting issues. However, only four of the 21 issues were single faceted.

An example of such an issue is Issue 6 in Table 5.1. It states that *there is a lack of understanding of the electrical system and software at the management level*. This is an issue that could be explained by the fact that many managers and other staff have a mechanical background. Educate management is a natural solution to this problem. However, the first step is probably to convince management that they need to be educated.

5.1.2 Cross Cutting Issues

The cross cutting issues could be complex in the sense that it might require more than one area to change to be successful in solving that particular issue. On the other hand trying to correct the problem in just one area might be enough. If that is the case, than a cross cutting issue might actually be easier to solve than a non cross cutting issue.

If an issue relates to organization and PMT, it could be that a change in the organization will make changes in other areas unnecessary. This is exemplified with Issue 12, *the complexity in the organization as well as the product has increased which has led to a situation where the existing processes are insufficient*. This issue is related to PMT as well as organization. However, a change in the organization might be enough to solve this issue, but it could also be that a organizational change will not solve this issue at all. Moreover, a change of process might be insufficient, and to be successful in solving this issue, both a change in process as well as organization could be required.

Issue 5, *there is a lack of clear long-term architectural strategy*, is an issue mapped to architecture and management. This issue will cause the architecture to become less evolvable and major revisions have to be made more often. To resolve this issue management needs to have a clear strategy on how the architecture should evolve over the years.

5.1.3 A Comparison of Issues Between Organizations

We believe that many issues are common for all three companies, but some more dominant in a particular organization. In this section we discuss differences and similarities in the companies based on how the issues were rated in the survey.

In Figure 5.1 a Venn diagram with the six most highly ranked issues from each company are included. As an example Issue 3, 4 and 14 are among the top ranked at all companies, while Issue 7 and 11 were only top ranked at V3P. This is a first step to analyze how different issues are reflected in each organization. The possibility to analyze the survey data statistically will be investigated in future research.

An unexpected finding is that VCE and V3P, that both are part of the Volvo Group, have no common issue among the six highest ranked ones. Instead VCC has common issues with both companies. One possibility could be that the culture of the organization and the business situation affects more than similarities in the product.

Significant issues for all companies

Issue 3, states that *architectural issues should be handled more energetically and it should be made clearer who in the organization is responsible for such issues*. The reason for why this is an issue at all three companies could be that architectural work is not prioritized from management. This further relates to the lack of understanding of E/E system development from management.

Most architecture work is usually made to comply with requirements from the vehicle project that has the earliest deadline and this will make the architecture hard to adopt for future vehicles without major revisions of the architecture.

Issue 4, states that *there is a lack of process for architecture development*. The architectural development at all companies today is ad-hoc. Without a process it is easy to make the same mistakes over again, or as one respondent said "we make the same mistakes in cycles of seven years". Related to this is Issue 14 stating that *architecture decisions are often made based on experience and gut feeling*.

A process for architectural work would most certainly ensure the use of more structured methods for decision making. Even if most decisions are made on gut feeling and experience, it does not mean the decisions made are bad. The reason that many decisions are made this way could be that the few methods that exist are not good enough as stated in Issue 10.

Figure 5.1: Relation of highly ranked issues between VCE, V3P and VCC.

Significant issues for VCC and V3P

Issue 1 states that *several brands and products share the same architecture but have different priority order between, for example, quality and cost.* This issue was more significant at VCC and V3P than at VCE. A reason why this is not a highly ranked issue at VCE could be that they do not share architecture between brands and models in the same way as V3P and VCC does. Further VCE only share architecture between vehicles under the Volvo brand compared to V3P and VCC that in some cases share architecture with for example Renault and Ford respectively.

Significant issues for VCC and VCE

Issue 10 concerns the *lack of method or model to evaluate the business value when choosing the architecture*. This issue was highly ranked at VCE and VCC but not at V3P. The reason for this is unclear since all three companies stated that most architectural decisions are based on gut feeling. However it could be that the interviewees at V3P do not see the need for changing the way decisions are made, or it could just mean that other issues were more important for them. As explained earlier this is a key issue when it comes to finding a solution to Issue 4.

Significant issues for VCC

At VCC Issue 20 was ranked among the top six stating that *processes and methods are less valued than knowledge and competence of individuals*. A possible reason why this issue is more highly ranked at VCC could be that some of the senior architects have been involved in almost all architecture design work for the last 20 years.

Significant issues for V3P

At V3P two issues were more significant, Issue 7, *there is no clear process for handling requirements*, and Issue 11, *it is unclear how to prioritize between time, cost and quality*. When it comes to requirements some respondents at V3P claimed that informal contacts are a crucial part when working with requirements. One reason why this is a problem at V3P could be that more than one brand tries to influence which requirements that should be considered.

Issue 11 seems to be a typical management problem. The priority order between these three factors is highly dependent on the latest quality report, or if the last quarterly report is not as good as expected the focus will be on reducing cost. We have not found any indications on why this issue was higher ranked at V3P than at VCE and VCC.

Significant issues for VCE

Two issues were considered more important at VCE than at VCC and V3P. The first one is Issue 12, *advanced engineering projects have low priority and to increase the priority they are merged into development projects too early*. A possible reason why this issue is highly ranked at VCE could be that although all three companies have advanced engineering departments, at VCE the advanced engineering activities are less prioritized. Instead advanced engineering projects are moved to delivery projects, which severely increase the uncertainty in the delivery project. One reason for the organization to often end up in this situation might be that development projects cannot keep their deadlines and are therefore utilizing resources that were allocated for advanced engineering projects.

Issue 19, *the complexity in the organization as well as the product has increased which has led to a situation where the existing processes are insufficient*, is the other issue that was more significant at VCE. A possible explanation to this could be that the extensive use software and electronics has been introduced more recently in a construction equipment than in a car or truck.

5.2 Effective Decisions

The first research question leaves us with many issues, but no clear solution to these issues. Our answer to the second research question might resolve some of the issues discussed in the previous section. The second research question was

RQ2: How to make effective decisions when adding new functionality to an existing electrical/electronic system architecture?

The result based on this question is a method that can aid in the decision making process when integrating new functionality. The method is fully described paper C, together with a guiding example.

Issues that might diminish by using this method is first of all the issue stating that *architecture decisions are often made based on experience and gut feeling* (Issue 14). The method could provide a positive influence on Issue 13 stating that *decisions are usually poorly motivated and it is hard to reach consensus and acceptance in a decision*.

The method provides a structured reasoning on how to choose between different integration strategies when adding new functionality to an existing electronic system architecture. An integration strategy is chosen based on what quality attributes are most important to that particular system. To extract these qualities we propose a light weight version of the Architecture Tradeoff Analysis Method (ATAM) [14]. To prioritize these qualities both against each other and how well they are suited for a particular integration strategy we use a variant of the Analytical Hierarchy Process (AHP) [15].

The method is flexible and scalable meaning it is possible to choose the number of people involved as well as the effort for each individual. It further provides some support to answering why a certain design alternative is chosen. If the "why" is clearly understood, we run a low risk that the decision is overrun by a new decision.

Chapter 6

Conclusions and Future Work

In this thesis we present issues that are related to automotive E/E system development. We have seen that these issues are relevant and that they are real issues at the companies studied. We cannot claim that we have found all issues that are related to automotive E/E system development but we believe that these are among the most important ones to consider to remain successful within each company's domain.

Even though many quite negative issues were found, the companies studied have been and still are very successful within their domain. Being able to discuss these issues in such an open manner is a way to start forming solutions to some of these issues. Through the investigations we have seen that these companies are very mature, being able to discuss and talk about issues instead of just using the "ostrich algorithm" [36].

When we presented our results at seminars with the companies we have seen a great interest in trying to fix these issues which further concludes that the issues are important to solve. We believe that some issues require new methods and models while some are more related to the actual organization at that particular company. What is clear though is that in the automotive industry there are many challenges due to the increasing amount of software and electronics in vehicles.

At the moment there is no indication that this exponential increase of software and electronics will stop within the next decade. Another trend is that there will be less but more powerful ECUs. This is due to physical limitation on where to place electronics. This implies that each ECU will contain more software, which means that when adding new functionality controlled by software and electronics, much of the complexity will move from the physical view of the architecture to the logical view. As mentioned in Section 2.2, the industry is much more comfortable dealing with the physical view than with the logical, hence this shift to software complexity is a growing problem.

As a possible solution to some of the issues identified we propose a method. It is presented in paper C and is a first step towards more structured decision making. Although the method was constructed before the actual case study was made we already had indications from discussions with experts in the automotive domain that there was a great need for such a method.

6.1 The Next Step

The main contribution in this thesis is the issues related to automotive E/E architecture development, and a first step is to make the organizations aware of the issues that exist. However, there is still a need to try to resolve these issues in order to make these companies even more successful. The next step is therefore to choose a few of the identified issues and find solutions to them. This might imply developing new methods and tools, but also suggest changes in processes or the organization.

Some of the proposed actions might not be suitable for academic research. An example of this could be the action that concerns management and their lack of understanding for E/E system development. In this case we believe that the company itself has to make most of the work. Actions that on the other hand are suitable for academic contributions are first of all the development of new methods that can aid in the process of making architectural decisions. These methods have to be both effective and efficient in order to be accepted by the industry.

Another area where academic research can be of great use for the automotive industry is how to create a clearer connection between the architecture and the business success for the company. Furthermore, the lack of processes for architectural development can be further elaborated by academia, focusing on usability for industry and still contribute academically.

The issues presented in this thesis are based on interviews from the automotive industry, but do the same issues exist in other industries? Our aim is to make a survey with companies outside the automotive industry to be able to claim that these issues are general for other industries. If that is the case then hopefully the same solutions are applicable.

Bibliography

[1] M. Broy, I.H. Kruger, A. Pretschner, and C. Salzmann. Engineering automotive software. *Proceedings of the IEEE*, 95(2):356–373, Feb. 2007.

[2] Gariel Leen and Donald Heffernan. Expanding automotive electronic system. In *IEEE Computer*, volume 35, pages 88–93, 2002.

[3] Bernd Hardung, Thorsten Kölzow, and Andreas Krüger. Reuse of software in distributed embedded automotive systems. In *EMSOFT '04: Proceedings of the 4th ACM international conference on Embedded software*, pages 203–210, New York, NY, USA, 2004. ACM.

[4] Pictures of the future. *The Magazine for Research and Innovation*, Fall 2005.

[5] IEEE Recommended Practice for Architectural Description of Software-Intensive Systems. IEEE 1471-2000, 2000.

[6] ISO 11898. Road vehicles - interchange of digital communication - controller area network (CAN) for high speed communication. *International Standards Organisation (*ISO*)*, ISO Standard-11898, November 1993.

[7] FlexRay Consortium. www.flexray.com.

[8] MOST Cooperation. Most - Media Oriented System Transport. www.mostcooperation.com.

[9] Nick Rozanski and Eoin Woods. *Software Systems Architecture*. Pearson Education, 2005.

[10] AUTOSAR AUTomotive Open System ARchitecture. www.autosar.org.

[11] Colin Robson. *Real World Research*. Blackwell publishing, second edition, 2002.

[12] Robert K Yin. *Case Study Research, Design and Methods*. SAGE Publications, Thousands Oak, California, 1986.

[13] Claes Wohlin, Per Runeson, Martin Höst, Magnus Ohlsson, Björn Regnell, and Anders Wesslén. *Experimentation in Software Engineering: An Introduction*. Springer, 2000.

[14] Rick Kazman, Mark Klein, and Paul Clements. ATAM: Method for architecture evaluation. Technical report, Carnegie Mellon Software Engineering Institute, CMU/SEI-2000-TR-004.

[15] S.H Yeo, M.W Mak, and A.P Balon. Analysis of decision-making methodologies for desirability score of conceptual design. *Journal of Engineering Design*, 15:195–208, 2004.

[16] Manfred Broy. Challenges in automotive software engineering. In *ICSE '06: Proceedings of the 28th international conference on Software engineering*, pages 33–42, New York, NY, USA, 2006. ACM.

[17] K. Grimm. Software technology in an automotive company - major challenges. *Software Engineering, 2003. Proceedings. 25th International Conference on*, pages 498–503, May 2003.

[18] Alexander Pretschner, Manfred Broy, Ingolf H Kruger, and Thomas Stauner. Software engineering for automotive systems: A roadmap. *Future of Software Engineering, 2007. FOSE '07*, pages 55–71, May 2007.

[19] Melvin E. Conway. How do committees invent? *Datamation*, april 1968.

[20] Dean Tjosvold. Cooperative and Competitive Interdependence: Collaboration Between Departments To Serve Customers. *Group Organization Management*, 13(3):274–289, 1988.

[21] Michael M Beyerlein, Sue Freedman, Craig McGee, and Linda Moran. The ten principles of collaborative organizations. *Journal of Organizational Excellence*, 22(2):51–63, April 2003.

[22] B. Graaf, M. Lormans, and H. Toetenel. Embedded software engineering: the state of the practice. *IEEE Software*, 20(6):61–69, Nov.-Dec. 2003.

[23] Kishore Sengupta, Tarek K. Abdel-Hamid, and Luk N. Van Wassenhove. The experience trap. *Harward Business Review*, 86(2):94–101, February 2008.

[24] Stefan Thomke and Takahiro Fujimoto. The effect of ’front-loading’ problem-solving on product development performance. *Journal of Product Innovation Management*, 17(2):128–142, March 2000.

[25] R. Bahsoon and W. Emmerich. An economics-driven approach for valuing scalability in distributed architectures. *Seventh Working IEEE/IFIP Conference on Software Architecture, 2008. WICSA 2008.*, pages 9–18, Feb. 2008.

[26] Agus Sudjianto and Kevin Otto. Modularization to support multiple brand platforms. In *Proceedings of DETC: ASME Design Engineering Technical Conferences*, Pittsburgh, USA, September 2001.

[27] J. Bosch. Product-line Architectures in Industry: A Case Study. *Proceedings of the* 21^{st} *International Conference on Software Engineering, Los Angeles, USA*, pages 544–554, 1999.

[28] J. Bosch and P. Molin. Software architecture design: evaluation and transformation. *IEEE Conference and Workshop on Engineering of Computer-Based Systems, 1999. Proceedings. ECBS ’99.*, pages 4–10, Mar 1999.

[29] P. Popp, M. DiNatale, P. Giusto, S. Kanajan, and C. Pinello. Towards a methodology for the quantitative evaluation of automotive architectures. *Design, Automation & Test in Europe Conference & Exhibition, 2007. DATE ’07*, pages 1–6, April 2007.

[30] A. Rajnak and A. Kumar. Computer-aided architecture design & optimized implementation of distributed automotive ee systems. *Design Automation Conference, 2007. DAC ’07. 44th ACM/IEEE*, pages 556–561, June 2007.

[31] Sri Kanajan, Haibo Zeng, Claudio Pinello, and Alberto Sangiovanni-Vincentelli. Exploring trade-off’s between centralized versus decentralized automotive architectures using a virtual integration environment. In *DATE ’06: Proceedings of the conference on Design, automation and test in Europe*, pages 548–553, 3001 Leuven, Belgium, Belgium, 2006. European Design and Automation Association.

[32] Alberto Sangiovanni-Vincentelli. Defining platform-based design. *EEDesign of EETimes*, February 2002.

[33] Felice Balarin, Luciano Lavagno, Claudio Passerone, Alberto L. Sangiovanni-Vincentelli, Marco Sgroi, and Yosinori Watanabe. Modeling and designing heterogeneous systems. In *Concurrency and Hardware Design, Advances in Petri Nets*, pages 228–273, London, UK, 2002. Springer-Verlag.

[34] F. Balarin, Y. Watanabe, H. Hsieh, L. Lavagno, C. Passerone, and A. Sangiovanni-Vincentelli. Metropolis: an integrated electronic system design environment. *Computer*, 36(4):45–52, April 2003.

[35] Robert G. Cooper. Stage-gate systems: A new tool for managing new products. *Business Horizons*, 33(3):44–54, May-June 1990.

[36] Andrew S Tanenbaum. *Modern Operating Systems*. Prentice Hall, second edition, 2001.

II

Included Papers

Chapter 7

Paper A: A Case Study of Issues Related to Automotive E/E System Architecture Development

Peter Wallin and Jakob Axelsson
Presented at the 15th IEEE International Conference on Engineering of Computer-Based Systems, Belfast, Northern Ireland, March, 2008

Abstract

The use of electronics in vehicles is increasing quickly and the systems are becoming increasingly complex. This makes the engineering of these advanced computer-based systems more and more difficult. In particular, finding a good architecture is a prerequisite for successful design. In this study we investigate key issues related to real-world decisions regarding a car's electrical and electronic system architecture. To extract the key issues an exploratory case study was performed at a car manufacturer. We used semi- formal interviews complemented with a survey to validate the results. The contribution of this paper is twelve issues that reflect the situation at a car manufacturer. Also, possible actions to deal with these issues are provided.

7.1 Introduction

The automotive industry has in recent years witnessed a dramatic increase in functionality based on electrical and electronic components. According to some sources, 80% of the innovation in a car in the premium segment comes from the electronics [1]. Many of the advances seen in the automotive industry, for instance in areas such as safety, emission control, comfort, and quality, would have been impossible without the use of advanced computer-based control systems. Also, electronics can be used to reduce cost, when expensive mechanical components are replaced by cheaper electronic controllers. However, there are many challenges related to developing these systems. In this paper, we present a case study that tries to establish how an automotive manufacturer deals with the development of the overall electrical and electronic (E/E) system architecture, and what important issues remain to be solved.

7.1.1 Context Description

Although the electronics has a great potential to improve vehicles, the systems are becoming increasingly complex and that makes the engineering of these advanced computer-based systems more and more difficult. The functions are in many cases safety critical, requiring special care to handle any circumstances that may possibly occur during operation. At the same time, the system has a very long life time where only sporadic maintenance can be assumed. The products are mass-produced, so assembly must also be very efficient. Some vehicles are also consumer products, which means that the price must be kept low.

Due to varying customer demands, but also due to different legal requirements in the countries in which the product is being sold, many variants of the product must be designed and verified. To handle this, and to be able to have reasonable production volumes of each system, the Original Equipment Manufacturers (OEMs) usually employ a platform strategy in which many components are common across a range of products. The platform is refined over many years, and each vehicle therefore has to cope with an extensive amount of legacy both in components and in the overall structure.

With this multiplicity of products and variants, the *architecture* is becoming very important and is a source of increasing interest from the OEMs. An architecture can be defined as the fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution [2]. Typically, the definition of the architecture is done early in the development phase, and is a prerequisite for the detailed system design. Therefore, architecture development is a key activity in which many important decisions are made directly or indirectly.

Many of the vehicle manufacturers are part of larger, multi-brand corporations, and this means that additional complexity is generated by sharing platforms, architectures, and systems across several brands, while still maintaining the uniqueness of each brand. Also, much of the system development is done by suppliers, and the main responsibility of the OEM is providing requirements and later integrate the different systems together. This further adds challenges to the development.

It should also be mentioned that the OEMs are very large organizations, in which thousands of engineers are involved in the development of a new vehicle. The suppliers are just as large, meaning that even more people participate in the complete project. Since the architecture is an integration activity, it is a place where many interests meet. Therefore, organizational and management issues are closely related to the architecture development.

7.1.2 Research Question

The purpose of this study is to get a deeper understanding of how decisions are made when developing the electronic system of a vehicle. In particular, we would like to improve the knowledge about factors involved in a real-world situation, in order to be able to later provide solutions that are realistic and effective.

The concrete research question we address is therefore as follows:

What are the key issues affecting real-world decisions regarding a car's electrical and electronic system architecture?

Naturally, the answer to this research question must be sought at the companies carrying out development of electronic architectures. Also, it cannot be assumed that only technical issues are related to this question, but also organization and management, as well as processes, methods, and tools must be considered.

7.1.3 Related Work

To assess an architectural approach or aid in selecting a specific architecture over another a number of methods exist. The problem with most of these methods is that they only consider technical aspects. Other considerations such as organization, cultural issues and the political situation at the particular company are usually ignored. To evaluate a software architecture and analyze how well it suits the business drivers ATAM [3] and CBAM [4] can be used. Both methods has been developed by the Software Engineering Institute at Carnegie Mellon. ATAM and CBAM has been developed for software architectures and only considers one architecture. Larses suggest a combination of keyfigure analysis, Design Structure Matrix (DSM) and qualitative reasoning. This model aids in designing the architecture and is described in [5]. Another method to evaluate an architecture is the Architectural Evaluation Method (AEM) in which requirements are analyzed to establish quality goals. This method is based on the ISO 9126-1 quality model [6]. The methods described above focus only on technical parameters. How to predict cost and business value for different architectures is discussed in [7] where cost is added to existing UML models and together with risk analysis and probability distributions Monte Carlo simulations are used to analyze the risk of not reaching the cost targets.

Even though many of these methods relate to industrial problems, few are used actively in the automotive industry today. There is also no or little documentation that these methods really solve today's issues with E/E system architecture development. We believe that there is a need to understand what the real issues are when developing E/E system architectures, before developing a new method or model. Our approach is therefore to investigate the current situation and what the real issues are, and as a second step focus on how to solve these issues. Different issues can have different solutions, where some may require new methods and models, some could require a process change.

7.1.4 Overview of the Paper

In the next section, we provide more details about the study, including the methodology used to answer the research question. Then in Section 8.3, the results of the study are presented and analyzed. In Section 8.4, the validity of the results are discussed. Possible actions concerning how to deal with the issues found are presented in Section 8.5. Finally, in Section 8.6, the conclusions are summarized and some directions for future research are proposed.

7.2 Methodology

The research question was addressed with an exploratory single case study. Exploratory studies reveal answers to questions based on what, how, and why. As our primary source of information we used semi-structured interviews. Semi-structured interviews have predetermined questions, but the order can vary based on the interviewert's perception of what seems most appropriate [8]. Additional questions can also be constructed during the interview and it is also possible to remove questions that seem inappropriate. Two persons were always present at the interviews, one mostly taking notes and the other one asking questions. We chose not to use any recording devices due to the risk of limiting the respondent's openness.

7.2.1 The Case at Volvo Cars

A suitable case study environment was found at Volvo Car Corporation (VCC), which is a partner together with two other OEMs in the research project in which this study was carried out. The company has its headquarters, including product development and many other functions, in Gothenburg, Sweden. The company is a producer of premium cars, with special focus on safety, environment, and quality. It has approximately 25,000 employees and manufactures and sells close to 500,000 vehicles each year worldwide. It has been a subsidiary of the Ford Motor Company (FMC) since 1999, and has close co-operation primarily with Ford of Europe in Germany and Jaguar-Land Rover in the UK. For these brands, VCC has a leading responsibility for the E/E architecture.

7.2.2 Planning and Preparations

The unit of analysis [9] for the case study was the E/E department within the Research & Development organization. At VCC seven people were selected by the second author of the paper, who is familiar with the organization. The people interviewed include a senior manager responsible for concept studies of E/E systems, a senior technical advisor working with strategies, a project manager for the E/E system in a vehicle project, a line manager responsible for some aspects of the system architecture, a technical leader responsible for key systems and functions in the architecture, and two engineers that develop functions and systems that utilize the architecture. We believe that this selection covers many aspects of the architecture development. After the selection was made and invitations were sent out, all contacts with the interviewees were handled by the first author, who has no relation to the company. None of the interviewees have any strong formal dependency to the authors and which reduces the risk to get insincere answers.

7.2.3 Interviews

All questions were semi-formal and asked in such a way that the respondent was encouraged to talk about what they thought important. An example of a question asked was *"How do you make architectural decisions today?"*. Questions were added based on the answers from the respondents. As mentioned above no recording devices were used to further ensure that the respondent spoke as freely as possible. Two researcher were present at all interviews, one taking notes and the other one asking most of the questions. All interviews lasted between 50 minutes up to 100 minutes and all notes was transcribed directly after each interview to avoid any misinterpretation of the notes made.
The interviews were anonymous and no names were printed on the transcripts. All names of respondents were kept in a separate file to be able to trace backwards in case the data needed to be complemented in any way.
Since the first language for all respondents is Swedish all interviews were also held in Swedish in order not to limit the answers.

7.2.4 Data Analysis

The data was extracted from the transcribed documents by categorizing data into a spreadsheet. The result from the data analysis was a long list of issues and factual statements. Similar issues were grouped together and a high level issue was constructed based on the low level issues. Each issue was constructed based on opinions from at least two respondents. A chain of evidence was upheld by a case study database as described by [9]. All data analysis was done by two researchers together enabling a discussion about how to interpret the data.

7.2.5 Validation

To validate that all identified issues were relevant we made a survey. Each respondent received a letter describing each issue. The respondent then placed a mark on a line to indicate how well the described issue matched their own opinion. The line ranged from "I do not agree at all" to "I agree entirely" and was 100 *mm* long. An example describing how the survey was designed is shown in Figure 8.1.

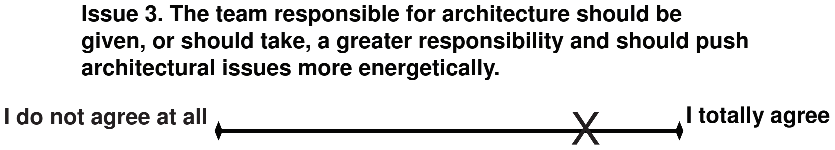

Figure 7.1: Example of survey design.

The survey used for validation can also be used to investigate if a respondent thinks an issue is important but did not state that clearly during the interview. All surveys were totally anonymous making it impossible to draw any conclusions about how different groups or roles answers differently. All seven interviewees answered the survey suggesting that they see these issues as relevant.

7.3 Results

In this section, the results of the case study are presented. First, we will list the issues that were elicitated from the interviews, and discuss their meaning in some detail. Then, in the second subsection, the results of the follow-up survey sent to the respondents are presented.

7.3.1 Identified Issues

Based on the interviews, a number of statements were collected, grouped, and categorized. After abstracting from similar statements, a total of 12 issues were identified. These were all issues that were mentioned by at least two different respondents. An overview of these issues and to what area they relate are shown in Table 7.1. The issues were the following ones (where the issue titles are the ones used in the survey, but have been translated from Swedish):

Issue 1. Several car brands share the same architecture but have different priority order between, for example, quality and cost.
The co-ordination of similar brands is a complex problem, and brands that share an architecture may have different priorities. In the case of Volvo Cars,

Table 7.1: Mapping of issues to high level attributes

Issue	**Architecture**	**Organization**	**Process, Methods& Tools**	**Management & Business**
1. Several car brands share the same architecture but have different priority order between, for example, quality and cost	**X**			**X**
2. There is a lack of clear strategy for what development should be done in-house and what should be done at external suppliers		**X**		**X**
3. The team responsible for architecture should be given, or should take, a greater responsibility and should push architectural issues more energetically	**X**	**X**		**X**
4. History has a large influence on architectural decisions, and is reflected both in choice of technology and in the organization	**X**	**X**	**X**	
5. There is a lack of clear long-term architectural strategy	**X**			**X**
6. There is a lack of method or model to evaluate the business value when choosing the architecture	**X**		**X**	
7. Architecture decisions are often made based on experience and gut feeling	**X**		**X**	
8. The modeling tools used today demand resources and provide little value			**X**	**X**
9. Decisions are easily made that suit one's own team or component		**X**		
10. There is a lack of process for architecture development	**X**		**X**	
11. Technical parameters are regarded as less important than cost when selecting components or suppliers			**X**	
12. There is a lack of understanding of the electrical system and software at the management level				**X**

the relation to Ford appears to be complicated. Volvo as a premium brand is driven more by the value of the product, whereas Ford as a mass-market brand is more focused on reducing cost. This leads to complications and thoughts on what can really be shared without each brand losing its identity.

Issue 2. There is a lack of clear strategy for what development should be done in-house and what should be done at external suppliers.
There are different opinions on how much influence a supplier should have. Sometimes the competence of a supplier is not fully used. On the other hand, with too much involvement the OEM will become tied to a certain supplier which makes it harder to switch to a new partner should the need arise. There are different strategies within the Ford Motor Company. The Ford brand often uses system suppliers whereas Volvo prefers to specify the details and design certain parts of the system themselves. Many suppliers try to move up the value chain by taking a larger responsibility for the integration which also can create tension.

Issue 3. The team responsible for architecture should be given, or should take, a greater responsibility and should push architectural issues more energetically.
It is not clear who is responsible for driving changes in the architecture. Many decisions are made bottom-up. The decisions are only made once a problem is present and there is a tendency to act reactively rather than proactively. Some respondents hinted that this situation may be due to the current organization, where certain aspects of the architecture are the formal responsibility of one team, and other aspects belong to another team.

Issue 4. History has a large influence on architectural decisions, and is reflected both in choice of technology and in the organization.
It is easy to get stuck in a historic pattern of reasoning when making architectural decisions, both in terms of organization and technology. There is a resistance to change and a tendency to "do as we have always done it". This is reflected in the fact that the current E/E architecture was fundamentally designed in the mid 1990s, and several of the persons involved in developing it are still part of the organization. Some respondents ask for an architecture that is more driven by current needs than by this legacy.

Issue 5. There is a lack of clear long-term architectural strategy.
There is a lack of clear strategy for how the architecture should look in the

future. A consequence of this is that new solutions sometimes are developed under stress with a result that does not appear satisfactory. Some respondents mentioned examples of attempts to cut cost on components leading to overload on networks and a late restructuring of the network topology.

Issue 6. There is a lack of method or model to evaluate the business value when choosing the architecture.
The connection between customer benefit and architectural decisions is hard to make, and the understanding of the relation between the architecture and the business is poor. A consequence is that many decisions are based on short-term cost requirements rather than long term strategic trends. One respondent indicated that this may be due to the fact that each vehicle project must carry its own cost, but sometimes an investment in the architecture does not give any benefits until later in the lifetime of the platform. A better model for sharing this kind of investment between vehicle projects is needed. The consequences of such event-driven development is that a cheaper product cost can result in a complex system that is costly to maintain in the long run.

Issue 7. Architecture decisions are often made based on experience and gut feeling.
Experience is important when it comes to understanding the architecture. Today, architectural decisions are often made by experienced individuals based on gut feeling. There is a lack of a structured method for making these decisions. It is not clearly stated in the interviews that this results in poor architectures, but nevertheless some respondents ask for better arguments and statistics as a basis for making these decisions.

Issue 8. The modeling tools used today demand resources and provide little value.
Many aspects are missed with the tools currently used in the organization. The tools focus on the functionality, but non-functional properties related to hardware or timing are not easily captured. The use of tools is thus considered to create extra work instead of making the job easier. One respondent also mentions that the tools have not been "marketed" enough in the organization, and many users have not been convinced about their benefits. (A description of the tools used at Volvo Cars for E/E development can be found in [10].)

Issue 9. Decisions are easily made that suit one's own team or component.

Sub-optimizations are common and the result is a more complex overall solution than is necessary. Each team optimizes for their needs and the cross-team improvements are not discovered. "Nobody is here to build a car, everybody is here to build their system", one respondent stated. He connects this situation to a reorganization a few years back, when the vehicle projects were deemphasized and the line organization was given more responsibility. The driver for this change was to improve commonality across vehicle lines.

Issue 10. There is a lack of process for architecture development.
There is not a clear and documented process for how the E/E architecture is developed. One respondent claimed that the process does not exist, another that it exists but is not well known within the organization.

Issue 11. Technical parameters are regarded as less important than cost when selecting components or suppliers.
The price strongly drives the choice of component. The purchasing department choose the supplier and sometimes technical parameters are traded for a lower price. This can sometimes lead to lower quality and hardware problems for modules mounted in a harsh environment. "You get what you pay for", as one respondent stated. On the other hand, the price is a very tangible parameter, whereas quality issues are often speculative at the time when the supplier choice is made.

Issue 12. There is a lack of understanding of the electrical system and software at the management level.
There is generally a lack of understanding of the electrical system and software in the organization outside the E/E department. Possibly; this is due to the fact that many managers and other staff have a mechanical background. The understanding improves over time, but only slowly.

7.3.2 Survey

The survey served two purposes: firstly to validate that all issues were correctly understood and secondly to investigate whether a respondent think an issue was important but did not state that clearly during the interview. Since the respondents marked their opinion on a scale of 100 mm all answers range from 0 to 100. A boxplot with outliers and distribution is shown in Figure 8.2.

The survey shows that for most issues the respondents agree, but there was disagreement in some cases. For example in Issue 8, that states; "the modeling

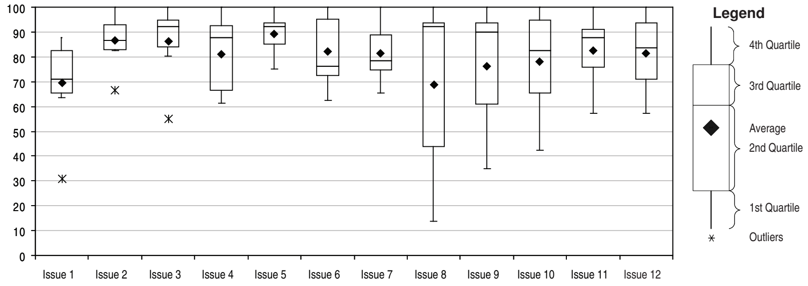

Figure 7.2: Boxplot showing responses to the survey.

tools are resource demanding and provide little value", the answers differs a lot. One explanation of this could be that respondents belong to different groups. Due to the fact that all surveys were completely anonymous we cannot draw any conclusions about who provided deviant replies.

7.4 Validity

An important aspect in case studies and interview studies is to ensure the validity. In the literature on research methodology, several different categories of validity are discussed. We mainly base our analysis on [9], but also complement it with more detailed guidelines from [11]. This section primarily concerns readers with extra interest in validity, and can therefore be skipped if no such interest exists.

7.4.1 Construct Validity

The construct validity is about ensuring that the construction of the study actually relates to the problem stated in the research question, and that the chosen sources of information are relevant.

A specific threat to construct validity is the use of unclear terms, and in this study the term "architecture" is a good example. We did not present the respondents with a clear definition of what we mean by architecture, but instead asked them what they mean by it. It is possible that some respondents answered the questions differently depending on their view of this concept. On the other hand, VCC uses the term extensively in their internal work, and if it were the case that employees view of architecture radically differs, that would be an issue in its own right. However, even though there are some variations in the view on architecture, we did not find any radically different opinions, which reduces this threat to validity.

Another possible threat is that the respondents guess what hypothesis the researchers had, and adapt their answers accordingly, for instance by exaggerating their opinions in an attempt to try to influence the outcome of the study. We tried to reduce this threat by using open ended questions in the interviews.

The analysis could also be influenced by the experimenter’s expectations. The second author is employed by VCC and has a long experience in the domain, and therefore he did not participate in the interviews to reduce the risk of influencing the respondents.

A possible threat is also that respondents may be hesitant to express their views if they could later be affected by their responses. The respondents did however not have any formal dependency on the researchers which also limits this threat. By guaranteeing anonymity, this risk is also reduced.

7.4.2 Internal and Conclusion Validity

Internal and conclusion validity concern the possibility to ensure that the actual conclusions drawn are true. In [9], it is stated that "internal validity is only a concern for causal (or explanatory) case studies". Our case study is explorative, and hence less sensitive to this threat. However, there are still issues that can be relevant to examine.

One has to do with the selection of respondents. The group used in the study is rather homogeneous in terms of personal characteristics, and also quite small. On the other hand, the full population (the E/E department at VCC) is also rather homogeneous and there is a limited number of persons that are closely involved in the architecture work. We tried to make a representative selection by ensuring that the participants had different roles in the organization.

With a small sample, there is a risk that a certain individual with a strong opinion can influence the result very much. We took two measures to try to compensate for this risk. The first was to only include issues that were mentioned by at least two persons. The other was to validate the identified issues with the survey.

On the other hand, the filtering of issues can lead to the opposite risk that we missed some valid conclusions. It could be that an issue is very important to the organization as a whole, but was not mentioned by more than one person. Therefore, based on this study we can only claim that we have found a number of important issues, but not that we have found all issues or even all the most important ones.

The issue of mortality (i.e., individuals who declined to participate) was not a major one in this study. Of the eight people initially contacted, only one was not able to be interviewed, due to scheduling difficulties, and all seven who were interviewed also completed the survey.

Another risk is related to "fishing", i.e., that the researchers consciously or unconsciously search for certain kinds of information. We tried to avoid this by having as open questions as possible in the interviews, and by finishing each interview by asking if the respondent felt that there was anything else that should be brought up.

In a survey, it is important to ensure that the instrument used is easy to understand for the respondents and does not cause any confusion in the interpretation. To reduce this risk, the survey was tested on three independent persons before sending it to the final respondents.

7.4.3 External Validity

External validity concerns how the results can be generalized. This is a specific concern for a case study, where it always can be discussed to what extent the observations are particular to a certain environment, or whether they are examples of general phenomenon.

The primary type of external validity is whether the conclusions can be generalized to a different organization, either within the same industry or in an different industry. We cannot with certainty say that this is the case, and to enable us to draw such conclusions further studies are needed.

7.4.4 Reliability

Reliability relates to the ability of others to replicate the study and arrive at the same results. A basis for replication is to have a well documented study design and well structured data collection, and we believe that this is the case for the study presented here. Assuming that the study were replicated and resulted in roughly the same transcripts of the interviews, it would still not guarantee that the resulting issues would be the same. There are different ways of interpreting the textual material, and in some cases there could be several ways of relating different statements to each other resulting in a different set of abstractions. We tried to reduce this risk by doing the analysis by having two people work together and discuss the structuring in detail. We therefore believe that a replicated study would come up with very similar issues, even though the exact wording or structuring could differ.

Another question is if we would get the same results in the same organization if we did the study at a different time. There are several possible reasons why the outcome could become different. One is that people tend to be heavily influenced by the latest events, and it was clear in the interviews that a few respondents were relating to a very recent vehicle project where there had been some architectural changes.

VCC has been going through a process of stepwise closer integration within Ford Motor Company over a number of years, and that has created a lot of work and discussion internally. At the time of the study, there were speculations in the press that Ford might consider selling VCC, and that could also have influenced the mindset of the participants. It is hard to judge the effects of such factors, but it is clear that a case study always measures a certain state of affairs, and over time reality changes so that a renewed study will give a slightly different result.

Also, it is expected that the organization will take notice of the issues identified, and try to improve them. Thus, the study itself may influence the study object in such a way that a replication at a later period in time is hard to fully accomplish.

7.5 Suggested Actions

In this section we show how the issues we have identified can be addressed. Issues are grouped together and we try to identify where the studied OEM are in the action tree shown in Figure 8.3. In the figure, we have marked by A, B and C where different issues are located. The figure further shows possible ways to take from where the organization is at the moment. It is possible for the organization to move both ways in this tree. For example the issues concerning Group B, as described below, where management needs to be educated to understand how software and electronics are developed. It could be that a reorganization takes place where a large part of the current management is replaced, causing Group B to move up the tree.

A: **Architectural business value model.** This group primarily concern issues 6, 7 and 8 but secondarily also issues 3, 4 and 11. This is related to the need for a method or model to see the business value of an architectural decision. At Volvo Cars they are aware of the problem but do not

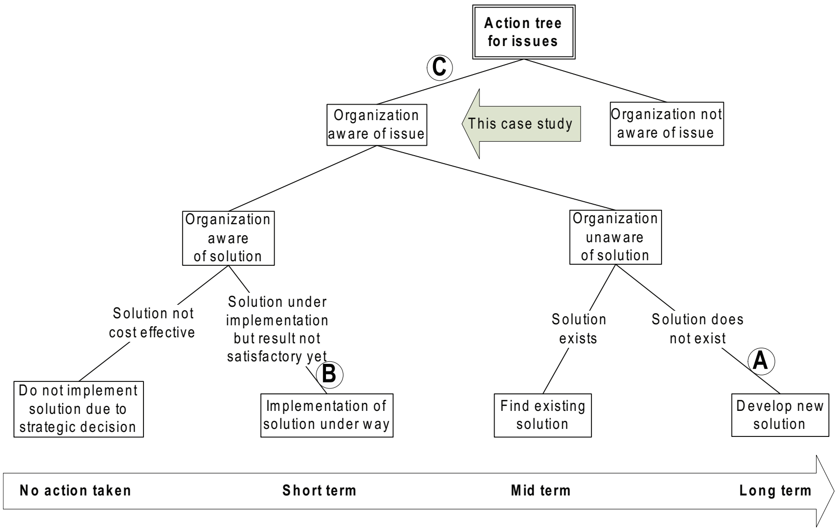

Figure 7.3: Possible actions for identified issues

know how to tackle the problem yet. We recommend that more research is put into this area to develop better models for business evaluation.

B: **Educate management.** The only issue directly connected to this group is issue 12. Also if we can increase the understanding from management on how software and electronics are developed all issues will be easier to take care of. There are some ongoing activities in this area, but we recommend that they should be escalated.

C: **Clarify architectural responsibilities.** Issues related to this group is first of all 3 and 10. Indirectly issue 5 and 9 can be related to this group. A process for architectural development is needed and different responsibilities must be made much clearer than today. We recommend that a process describing different responsibilities is developed. Further, more responsibility should be given to the architecture group.

Issue 1 and 2 cannot be solved within the electrical and electronic department and must be handled on a global company level.

7.6 Conclusion & Discussion

The complexity of automotive electrical and electronic systems is increasing rapidly. This makes the engineering of these advanced computer-based systems more and more difficult. In particular, finding a good architecture is a prerequisite for successful design.

In this case study we have identified and validated twelve issues that are related to real-world decisions regarding a car's electrical and electronic system architecture. We have shown that these issues are relevant but we cannot say that this is an exclusive set of issues when developing electronic and electrical system architecture.

Many of the identified issues are not just technical issues but they also relate to management and organization. The result has been validated by a survey and we can be certain that we have found issues that reflect the situation at the studied OEM. Also we believe that the result are general for the automotive domain. We base this last finding on informal meetings with other OEMs but further studies are needed to conclude whether these issues can be generalized to other OEMs or not.

7.6.1 Future Work

To continue the investigation of issues that are related to electrical and electronic system development we will continue with interviews at other automotive OEM's. Interviews have already started at an OEM developing trucks and will continue at an OEM developing construction equipment. This will hopefully give us the ability to generalize the result and get an exclusive set of issues that are related to electrical and electronic system development.

7.7 Acknowledgement

The authors would like to thank the E/E department at Volvo Cars and in particular all persons that participated in the interviews, making this study possible. Also a special thanks goes to Ana Magazinovic at Chalmers University of Technology who helped with taking notes and discussions about the context of this study.

Bibliography

[1] Gariel Leen and Donald Heffernan. Expanding automotive electronic system. In *IEEE Computer*, volume 35, pages 88–93, 2002.

[2] IEEE Recommended Practice for Architectural Description of Software-Intensive Systems. IEEE 1471-2000, 2000.

[3] Rick Kazman, Mark Klein, and Paul Clements. ATAM: Method for architecture evaluation. Technical report, Carnegie Mellon Software Engineering Institute, CMU/SEI-2000-TR-004.

[4] Rick Kazman, J Asundi, and Mark Klein. Making architecture design decisions: An economic approach. Technical report, Carnegie Mellon Software Engineering Institute, CMU/SEI-2002-TR-035.

[5] Ola Larses. *Architecting and modeling of automotive embedded systems*. PhD thesis, Royal Institute of Technology, 2005.

[6] *ISO/IEC 9126-1:2001, Software engineering - Product quality*.

[7] Jakob Axelsson. Cost models with explicit uncertainties for elextronic architecture trade-off and risk analysis. In *INCOSE 2006 Annual International Symposium on Systems Engineering,* Orlando, USA, July 2006.

[8] Colin Robson. *Real World Research*. Blackwell publishing, second edition, 2002.

[9] Robert K Yin. *Case Study Research, Design and Methods*. SAGE Publications, Thousands Oak, California, 1986.

[10] M Rhodin, L Ljungberg, and U Eklund. A method for model based automotive software development. In *2th Euromicro Conference on Real-Time Systems, Stockholm, 2002*, pages 15–18, 2002.

[11] Claes Wohlin, Per Runeson, Martin Höst, Magnus Ohlsson, Björn Regnell, and Anders Wesslén. *Experimentation in Software Engineering: An Introduction*. Springer, 2000.

Chapter 8

Paper B: Issues Related to Development of E/E Product Line Architectures in Heavy Vehicles

Peter Wallin, Stefan Johnsson and Jakob Axelsson

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Abstract

The amount of electronics in vehicles is growing quickly, thus systems are becoming increasingly complex which makes the engineering of these software intensive systems more and more difficult. In the automotive industry the use of product line architectures enables a set of vehicles to share architecture to decrease cost and increase quality. In this study we investigate key issues related to real-world decisions regarding electrical and electronic product line architecture for heavy vehicles. To extract key issues a multiple exploratory case study at two heavy vehicle manufacturers was performed. We used semi-formal interviews complemented with a survey to validate the results. The contribution of this study is 14 issues that reflect the situation at the two companies. Many of the identified issues relate to non technical areas such as organization, process, methods and tools, and management. Moreover, possible actions to deal with these issues are discussed.

8.1 Introduction

The automotive industry has in recent years witnessed a dramatic increase in functionality based on electrical and electronic components. According to some sources, 80% of the innovations in a vehicle come from electronics [1]. Many of the advances seen in the automotive industry, for instance in areas such as safety, emission control, comfort, and quality, would have been impossible without the use of advanced computer-based control systems. Also, electronics can be used to reduce cost, when expensive mechanical components are replaced by cheaper electronic controllers. However, there are many challenges related to developing these systems. In this paper, we present a case study that tries to establish how two different heavy vehicle manufacturers deal with the development of the overall electrical and electronic (E/E) system architecture, and what important issues remain to be solved.

8.1.1 Context Description

Although the electronics has a great potential to improve vehicles, the systems are becoming increasingly complex and that makes the engineering of these advanced computer-based systems more and more difficult. The functions are in many cases safety critical, requiring special care to handle any circumstances that may possibly occur during operation. At the same time, the system has a very long life time where only sporadic maintenance can be assumed. The products are mass-produced, so assembly must also be very efficient. Due to the fact that almost all heavy vehicles are sold business to business the customer puts extra consideration in the overall profitability of the product, instead of just the cost of purchasing the vehicle. Quality attributes such as availability and maintainability are important factors in reaching profitability for this kind of products.

Due to varying customer demands, but also due to different legal requirements in the countries in which the products are being sold, many variants of the product must be designed and verified. To handle this, and to be able to have reasonable production volumes of each system, the Original Equipment Manufacturers (OEMs) usually employ a platform strategy in which many components are common across a range of products. A platform is normally refined over many years, and each vehicle therefore has to cope with an extensive amount of legacy both in components and in the overall structure.

With this multiplicity of products and variants, the *architecture* is becoming very important and is a source of increasing interest for the OEMs. An architecture can be defined as the fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution [2]. An automotive electronic system architecture can be described in many ways using different views. A common view used is the *physical view* showing where the different Electronic Control Units, ECU:s, are physically placed and also shows how they are connected to each other via different networks with protocols such as CAN, Flexray, MOST etc.

Another view that is important is the logical view. The *logical view* describes logical relationships and how different components depend on each other logically. The logical view is independent of the physical view. However there might be physical limitations that will favor a different logical solution.

A view that is more unique for an automotive E/E architecture compared to general software architecture is the *electrical view*. This view shows the electrical distribution in form of cabling, fuses and power generation and storage.

Typically, the definition of the architecture is done early in the development phase, and is a prerequisite for the detailed system design. Therefore, architecture development is a key activity in which many important decisions are made directly or indirectly.

Many of the vehicle manufacturers are part of larger, multi-brand corporations. This means that additional complexity is generated by sharing platforms, architectures, and systems across several brands, while still maintaining the uniqueness of each brand. Also, much of the system development is done by suppliers, and the main responsibility of the OEM is providing requirements and later integrating the different systems together. This further adds challenges to the development.

It should also be mentioned that the OEMs are very large organizations, in which thousands of engineers are involved in the development of a new vehicle. The suppliers are just as large or sometimes even larger than the OEM, meaning that even more people participate in the complete project. Since the architecture is a basis for integration activities, it is a place where many interests meet. Therefore, organizational and management issues are closely related to the architecture development.

8.1.2 Research Question

The purpose of this study is to get a deeper understanding of how decisions are made when developing the electronic system of a vehicle. In particular, we would like to improve the knowledge about factors involved in a real-world situation, in order to be able to later provide solutions that are realistic and effective.

The concrete research question we address is therefore as follows:

What are the key issues affecting real-world decisions regarding a heavy vehicle's electrical and electronic system architecture?

With real-world we mean not only an industrial setting, but also what the people in that industrial setting consider to be the most important issues. Hence, it is how people perceive the current situation at that particular company we focus in this study.

Naturally, the answer to this research question must be sought at the companies carrying out development of electronic architectures. Also, it cannot be assumed that only technical issues are related to this question, but also organization and management, as well as processes, methods, and tools must be considered.

8.1.3 Related Work

The connection between the architecture and business objectives is often hard to find. However, changing the business objectives will influence areas like organization and process. It is therefore important to understand these dependencies between business objectives, architecture, organization, and processes [3]. A method to visualize these dependencies are described in [4]. The work is related to what Van der Linden et al. discusses in [5] and in a different context in [6].

To assess an architectural approach or aid in selecting a specific architecture over another, a number of methods exist. The problem with most of these methods is that they only consider technical aspects. Other considerations such as organization, cultural issues and the political situation at the particular company are usually ignored even if it is stated in [7] that it is even harder to deal with these non technical factors.

To evaluate a software architecture and analyze how well it suits the business drivers the Architectural Trade-off Analysis Method (ATAM) [8] can be used. It has been developed for software architectures and only consider one architecture. Larses suggests in [9] a combination of keyfigure analysis, similar to balanced scorecard [10], Design Structure Matrix (DSM) [11] and qualitative reasoning resulting in a model that aids in designing the architecture. Another method to evaluate an architecture is the Architectural Evaluation Method (AEM) [12] in which requirements are analyzed to establish quality goals. This method is based on the ISO 9126-1 quality model [13]. The methods described above focus only on technical parameters. How to predict cost and business value for different architectures is discussed in [14] where cost is added to existing UML models and together with risk analysis and probability distributions Monte Carlo simulations are used to analyze the risk of not reaching the cost targets.

Even though many of these methods relate to industrial problems, few are used actively in the automotive industry today. There is also no or little documentation that these methods really solve today's issues with E/E system architecture development. We believe that there is a need to understand what the real issues are when developing E/E system architectures, before developing a new method or model.

Our approach is therefore to investigate how the current situation and what the real issues are, and as a second step focus on how to solve these issues. Different issues can have different solutions, where some may require new methods and models, and others could require a process change.

The contribution of this paper is therefore a number of issues that reflect the situation at the two automotive companies. Many of the identified issues relate to non technical areas such as organization, process, methods and tools, and management. Moreover, possible actions to deal with these issues are discussed. Although many of the issues and actions have been identified separately in various papers for different industries, we provide a current state of what the key issues in the automotive industry are.

Further references that are related to specific findings of this study are described in Section 8.3.

8.1.4 Overview of the Paper

In the next section, we provide more details about the study, including the methodology used to answer the research question. Then in Section 8.3, the results of the study are presented and analyzed. In Section 8.4, the validity of the results are discussed. Possible actions concerning how to deal with the issues found are presented in Section 8.5. Finally, in Section 8.6, the conclusions are summarized and some directions for future research are proposed.

8.2 Methodology

The research question was addressed with an exploratory multiple case study. Exploratory studies reveal answers to questions based on what, how, and why.

As our primary source of information we used semi-structured interviews. Semi-structured interviews have predetermined questions, but the order can vary based on the interviewer's perception of what seems most appropriate [15]. Additional questions can also be constructed during the interview and it is also possible to remove questions that seem inappropriate.

8.2.1 Volvo 3P

One of the two companies involved in this study is Volvo 3P (V3P). V3P is a division within the Volvo Group responsible for product planning, product development, purchasing, and product range management for the three truck brands that are owned by the Volvo Group (Mack Trucks, Renault Trucks and Volvo Trucks). The development is focused to Gothenburg, Sweden but some activities are done in the United States and France. In total there are around 3,000 employees at V3P and the sales volume is approximately 220,000 trucks per year. The E/E department involves roughly 600 employees.

8.2.2 Volvo Construction Equipment

Volvo Construction Equipment (VCE) develops and manufactures all kinds of construction equipment such as; wheel loaders, excavators, articulated haulers, and graders. Responsible for the E/E system development is the component division of VCE. At VCE around 16,000 people are employed and approximately 140 are directly involved with E/E development.

Although both VCE and V3P are part of the Volvo Group they have limited cooperation and have their own business strategies. Further VCE has different legal requirements than V3P since VCE is to 90 % a manufacturer of off-road machinery. Furthermore VCE has more product variants and at the same time lower sales volumes than V3P.

8.2.3 Planning and Preparation

The unit of analysis [16] for the case study was the E/E development at the different companies. At VCE eleven people were selected, and at V3P ten. All persons were selected by a contact in the company with extensive knowledge about each organization and therefore suitable to choose people with different roles within the company. The people interviewed included a project manager, a technical leader, a senior technical advisor, a system architect, a software architect, a senior manager, and a technical expert. Both companies have a matrix organization and roles from both the line and project organizations were included. We believe that this selection covers all major aspects of the architecture development. After the selection was made, invitations were sent out and interviews booked. None of the interviewees have any strong formal relationship to the authors or the different contacts at each company, which reduces the risk to get insincere answers.

8.2.4 Interviews

All interviews were semi-formal and questions were asked in such a way that the respondent was encouraged to talk about what they thought important. An example of a question asked was *"How do you make architectural decisions today?"*. Questions were added based on the answers from the respondents, and there were very large differences between different interviews regarding what topics were discussed and how much time was spent on each area. No recording devices were used to further ensure that the respondent spoke as freely as possible. Two researchers were present at all interviews, one taking notes and the other one asking most of the questions. All interviews lasted between 70 and 120 minutes and the average time for interviews was 100 minutes. All notes were transcribed directly after each interview to avoid any misinterpretation of the notes made.

The interviews were anonymous and no names were printed on the transcripts. All names of respondents were kept in a separate file to facilitate traceability in case the data needed to be complemented in any way.

8.2.5 Data Analysis

The data was extracted from the transcribed documents by categorizing data into a spreadsheet. The result from the data analysis was a long list of issues and factual statements. Similar issues were grouped together and a high level issue was constructed based on the low level issues. Each high level issue was constructed based on opinions from at least two respondents. A chain of evidence was upheld by a case study database as described by Yin in [16]. All data analysis was done by two researchers together enabling a discussion about how to interpret the data.

8.2.6 Validation

To validate that all identified issues were relevant a survey was conducted. Each respondent received a letter describing each issue. The respondent then placed a mark on a line to indicate how well the described issue matched their own opinion. The line ranged from "I do not agree at all" to "I agree entirely" and was 100 *mm* long. The reason for using a continuous scale is that we intend to collect survey data from other companies and with a continuous scale more powerful analysis methods can be used [17]. If the respondent considered that he or she had insufficient knowledge about an issue, the option "No opinion" could be marked. An example describing how the survey was designed is shown in Figure 8.1.

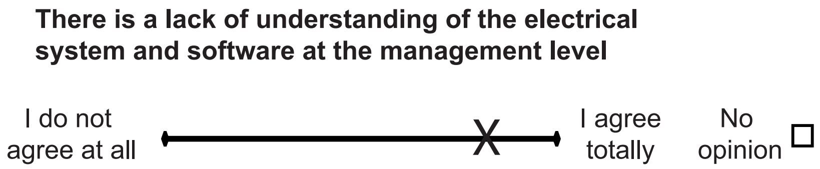

Figure 8.1: Example of survey design.

The survey used for validation can also be used to investigate if a respondent thinks an issue is important but did not state that clearly during the interview. Out of 20 surveys sent out 17 interviewees answered.

8.3 Results

In this section, the results of the case study are presented. First, we will list the issues that were elicited from the interviews, and discuss their meaning. Then, in the second subsection, the results of the follow-up survey sent to the respondents are presented.

It is important to note that what we measure is the subjective understanding of the situation of the company, as perceived by people in the organization with extensive knowledge about the architecture development. However, we believe there are good reasons to assume that this correlates well with the company's actual performance, even though we cannot show this formally.

8.3.1 Identified Issues

Based on the interviews, a number of statements were collected, grouped, and categorized. After abstracting from similar statements, a total of 14 issues were identified. These were all issues that were mentioned by at least two different respondents. Below each of the 14 issues are described.

Issue 1. Several brands and products share the same architecture but have different priority order between, for example, quality and cost.
Coordination of different brands and products is a complex problem. Brands and products that share an architecture have different priorities. Some brands focus more on cost and want to choose the cheapest alternative while others see more to the value that is created. This creates complications and thoughts around how much can be shared without the brands losing their identity. This issue was found at both companies. In [18] there is a discussion about brand identity and commonality but more from a functional perspective.

Issue 2. There is a lack of process for architecture development.
There is not a clear and documented process for how the E/E architecture is developed. This could be related to the fact that it is hard for management to see any real benefits from a structured architectural work. Also the architecture is seldom connected to customer needs which make it harder to motivate architectural development. This issue was also found at both companies. In another interview performed by Graaf [19] focusing on consumer electronics, the same issue was identified. Without an architectural process there is a big risk that the architecture is not documented properly which is a prerequisite to be successful in a product line architecture [20].

Issue 3. There is a lack of understanding of the electrical system and software at the management level.
There is generally a lack of understanding of the electrical system and software in the organization outside the E/E department. Possibly, this is due to the fact that many managers and other staff have a mechanical background. The understanding improves over time, but only slowly. Historically both companies have strong roots in development and manufacturing of mechanical products and as some interviewees stated "we are still a nuts and bolts company". This issue was more predominant at VCE then at V3P. A reason for this could be that V3P has put a lot of effort into trying to educate management in software and systems engineering. This issue is supported by [19] stating that systems engineering is mostly driven from a mechanical and electronic point of view

and seldom from a software perspective. In our case the systems engineering was driven from a mechanical view and not considering either software or electronics.

Issue 4. There is no clear process for handling requirements.
There is no clear process for how requirements should be collected. It is quite common to come up with a pure "wish list" and more effort should be made to investigate each requirement instead of relying on gut feeling. Informal contacts are an important part of working with requirements today. This issue was found at both companies. Another study [21] confirms that this issue is valid outside the automotive industry and that there is a specific need for clear prioritization of requirements.

Issue 5. The cooperation between product development and product planning needs to be improved.
The interface between product development and product planning is not clear. Product planning is spread out and is uncoordinated and at the same time the communication from the electronics department needs to be more coordinated. This issue was only found at V3P, and this could be heavily dependent on the background of the interviewees. Many of the in interviewees at VCE do not have any direct contact with product planning. In [22] the importance of cooperation between different departments are discussed.

Issue 6. There is no method or model for measuring and follow up of quality problems during development.
Lack of quality is not identified until the product reaches the market. Today, the actual quality achieved is not seen until late in the development process. For example, it is unclear how much a quality issue costs compared to choosing a more reliable and expensive component from the beginning. This issue was also only found at V3P.

Issue 7. There is a lack of method or model to evaluate the business value when choosing the architecture.
The connection between customer benefit and architectural decisions is hard to make, and the understanding of the relation between the architecture and the business is poor. A consequence is that many decisions are based on short-term cost requirements rather than long term strategic trends. Many respondents indicated that this may be due to the fact that each vehicle project must carry its own cost, but sometimes an investment in the architecture does not give any

benefits until later in the lifetime of the platform. A better model for sharing this kind of investment between vehicle projects is needed. The consequence of such event-driven development is that a cheaper product cost can result in a complex system that is costly to maintain in the long run. This issue was only found at VCE. In [23] they state that there is a need for such model for product line architectures but none existing yet. This issue is probably valid in many domains although it might not be possible to create a model that satisfies the need for many domains. For example in [24] three approaches to value based software reuse is suggested.

Issue 8. It is unclear how to prioritize between time, cost and quality.
The official position at the companies is that quality is the most important factor but in reality it is usually time. This is due to a decision for the start of production date early in the development process. The start of production date is often based on new legal requirements which mean that if these deadlines cannot be met the number of sold units will be zero until these regulations are fulfilled. This issue concerns prioritization of the overall vehicle project while issue 1 is about trade-offs in the architecture.

Issue 9. The complexity in the organization as well as the product has increased which has led to a situation where the existing processes are insufficient.
Clear processes and documentation is particularly important in a large organization and these areas have not been adapted in the same pace as the organization has grown. Both organizations have grown extensively during the past years, both organically and by purchasing other companies. Especially the E/E department at the different companies has grown and new requirements for incorporating different brands and products in the same E/E platform have arise.

Issue 10. Decisions are usually poorly motivated and it is hard to reach consensus and acceptance in a decision.
Decisions are often based on gut feeling and poorly motivated. When a decision finally has been made it is hard to get people to accept them. This sometimes leads to decisions being brought up again for discussion. This could be a trust issue based on unsuccessful projects in the past. The issue was found in both companies.

Issue 11. Decisions are easily made that suit one's own project, team or component even though it leads to a poorer overall solution.

Sub-optimizations are common and sometimes lead to a more complex overall solution than necessary. Optimization is made within one's own project or team and does not consider the potential of a favorable overall optimization. Each project is supposed to carry its own cost and this means that no one is prepared to compromise in favor of commonality. Everyone thinks that commonality is good as long as "my project" doesn't have to adapt in any way. This relates to Conway's law [25] from 1968 that says: "Any organization which designs a system will inevitably produce a design whose structure is a copy of the organization's communication structure". This issue was only found at VCE. VCE has an outspoken strategy that they should enhance commonality as much as possible. A problem is that there are no clear directions from top management how to achieve this.

Issue 12. Advanced engineering projects have low priority and to increase the priority they are merged into development projects to early.
Too little effort is put into advanced engineering projects or early concept and technology development. The projects are included too early in a delivery project to increase the attention and priority of the project. This is due to the fact that many resources are spent in the end of the delivery project making the advanced engineering projects short on resources. This severely increases the uncertainty in the delivery project. This issue was found at VCE. A more structured way of dealing with advanced engineering projects and stricter demands about when an advanced engineering project should be allowed in a vehicle project is needed and also it would be beneficial to try to move from back load to front load development. A problem is that legal requirements might force an advanced engineering project to be included earlier than what is preferable. One reason that the organization usually ends up in this situation might be that old development projects cannot keep their deadlines and are therefore utilizing resources that were allocated for advanced engineering projects. This issues with a possible solution is discussed in [26].

Issue 13. Processes and methods are less valued then knowledge and competence of individuals.
Today the development is highly dependent on individuals and the company rely on their knowledge. It is far from all projects that write white books [1] and even if a white book is written, it is seldom used as input to the next project. Information follows individuals and this leads to "hero based" development. It

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[1] In the white book project drawbacks and success are summarized. This document should always be used as input to the next project according to the companies development process.

is of course important to know what knowledge and competence is available inside the company but it is dangerous to rely on that this competence can replace processes and methods. This issue was only found at VCE.

Issue 14. Prestige and rivalry complicates cooperation between different departments and business units. There is a mismatch between some business units. This is to a large extent caused by the lack of clear guidelines from management what each business unit is responsible for. This rivalry and prestige is even clearer when it comes to higher management. This issue was found at VCE and it is in particular between two divisions that these problems arise. In [27] an interview study from an e-commerce software developer a similar issue was found.

8.3.2 Survey

The survey served two purposes: firstly to validate that all issues were correctly understood and secondly to investigate whether a respondent thinks an issue was important but did not state that clearly during the interview. Since the respondents marked their opinion on a scale of 100 mm all answers range from 0 to 100. Only one respondent used the "No Opinion" alternative on one question. A boxplot with outliers and distribution is shown in Figure 8.2.

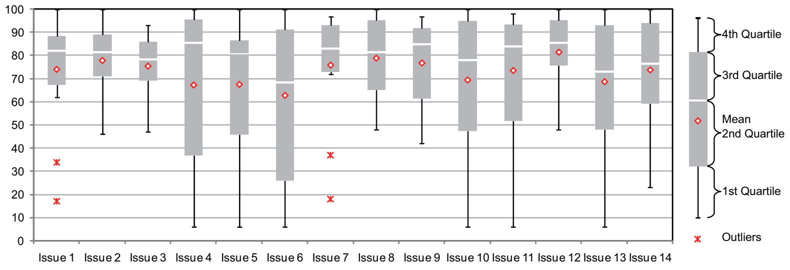

Figure 8.2: Boxplot showing responses to the survey.

The survey shows that for most issues the respondents agree, but there was disagreement in some cases. For example in Issue 6, that states; "There is no method or model for measuring and follow up of quality problems during development", the answers differ a lot. One explanation of this could be that respondents belong to different groups and that the respondents interpreted the statement differently. A reason for the variance could be that the data is from two different companies but further analysis shows that the reason more likely is due to different roles within each company.

8.4 Validity

An important aspect in case studies and interview studies is to ensure the validity. In the literature on research methodology, several different categories of validity are discussed. We mainly base our analysis on [16], but also complement it with more detailed guidelines from [28].

8.4.1 Construct Validity

The construct validity is about ensuring that the construction of the study actually relates to the problem stated in the research question, and that the chosen sources of information are relevant.

A specific threat to construct validity is the use of unclear terms, and in this study the term *architecture* is a good example. We did not present the respondents with a clear definition of what we mean by architecture, but instead asked them what they mean by it. It is possible that some respondents answered the questions differently depending on their view of what an architecture is, but since we did not find any radically different opinions this threat is reduced.

Another possible threat is that the respondents guess what hypothesis the researchers had, and adapt their answers accordingly, for instance by exaggerating their opinions in an attempt to try to influence the outcome of the study. We tried to reduce this threat by using open ended questions in the interviews.

A possible threat is also that respondents may be hesitant to express their views if they could later be affected by their responses. The respondents did however not have any formal dependency on the researchers which also limits this threat. By guaranteeing anonymity, this risk is also reduced.

8.4.2 Internal and Conclusion Validity

Internal and conclusion validity concern the possibility to ensure that the actual conclusions drawn are true. In [16], it is stated that "internal validity is only a concern for causal (or explanatory) case studies". Our case study is explorative, and hence less sensitive to this threat. However, there are still issues that can be relevant to examine.

One has to do with the selection of respondents. The group used in the study is rather homogeneous in terms of personal characteristics. We tried to make a representative selection by ensuring that the participants had different roles in the organization.

With a fairly small sample, there is a risk that a certain individual with a strong opinion can influence the result very much. We took two measures to try to compensate for this risk. The first was to only include issues that were mentioned by at least two persons. The other was to validate the identified issues with the survey.

On the other hand, the filtering of issues can lead to the opposite risk that we missed some valid conclusions. It could be that an issue is very important to the organization as a whole, but was not mentioned by more than one person. Therefore, based on this study we can only claim that we have found a number of important issues, but not that we have found all issues or even all the most important ones.

The issue of mortality (i.e., individuals who declined to participate) was not a major one in this study. Of the 22 people initially contacted, only two were not able to be interviewed, due to scheduling difficulties. 17 out of the 20 that were interviewed also completed the survey.

Another risk is related to "fishing", i.e., that the researchers consciously or unconsciously search for certain kinds of information. We tried to avoid this by using open-ended questions in the interviews, and by finishing each interview by asking the respondent whether there was anything else that should be discussed.

In a survey, it is important to ensure that the instrument used is easy to understand for the respondents and does not cause any confusion in the interpretation. To reduce this risk, the survey was similar to one used in an earlier study, presented in [29], with similar context.

8.4.3 External Validity

External validity concerns how the results can be generalized. This is a specific concern for a case study, where it always can be discussed to what extent the observations are particular to a certain environment, or whether they are examples of general phenomenon.

The primary type of external validity is whether the conclusions can be generalized to a different organization, either within the same industry or in a different industry. Based on the literature we can say that many of the issues are valid for other domains as well.

8.4.4 Reliability

Reliability relates to the ability of others to replicate the study and arrive at the same results. A basis for replication is to have a well documented study design and a well structured data collection, and we believe that this is the case for the study presented here. Assuming that the study were replicated and resulted in roughly the same transcripts of the interviews, it would still not guarantee that the resulting issues would be the same. There are different ways of interpreting the textual material, and in some cases there could be several ways of relating different statements to each other resulting in a different set of abstractions. We tried to reduce this risk by doing the analysis by having two people work together and discuss the structuring in detail. We therefore believe that a replicated study would come up with very similar issues, even though the exact wording or structuring could differ.

Another question is if we would get the same results in the same organization if we did the study at a different time. There are several possible reasons why the outcome could become different. One is that people tend to be heavily influenced by the latest events, and it was clear in the interviews that a few respondents were relating to a very recent vehicle project where there had been some architectural changes and turbulence.

Also, it is expected that the organization will take notice of the issues identified, and try to improve them. Thus, the study itself may influence the study object in such a way that a replication at a later period in time is hard to fully accomplish.

8.5 Suggested Actions

In this section we show how the issues we have identified could be addressed by the companies in the future. Issues are grouped together and we try to identify where the studied OEMs are in the action tree shown in Figure 8.3. In the figure, we have marked A-E where different issues are located. The figure further shows possible ways to take from where the organization is at the moment. It is possible for the organization to move both ways in this tree. For example the issues concerning Group B, as described below, where management needs to be educated to understand how software and electronics are developed. It could be that a reorganization takes place where a large part of the current management is replaced, causing Group B to move either up or down the tree.

Based on the study we propose both companies to take the following actions:

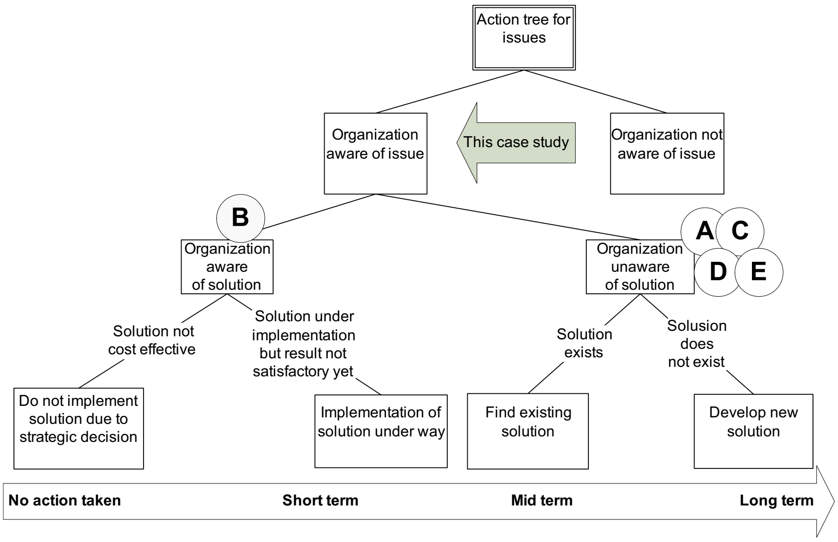

Figure 8.3: Possible actions for identified issues

A: **Clarify responsibilities in the organization.** Issues that relate to this group are issue 11 and 14. Both these issues could be solved by clarifying who is responsible for what and also focus less in the individual projects, and more on the overall business. Instead of trying to do what is best for the company, everyone prioritizes the success of their own project and is secondarily concerned about the success of the company. To resolve this, clear guidelines from management are needed, both about responsibilities and authorities. A barrier for this is the complex interdependencies between different parts both in the organization and in the system, as described in Conway's law [25].

B: **Educate management.** The only issue directly connected to this group is issue 3. Also if we can increase the understanding from management on how software and electronics are developed all issues will be easier to take care of. There are some ongoing activities in this area, but we recommend that they should be escalated. A possible barrier for succeeding with implementing this action is that the addition of software and electronics increases the complexity of the overall systems. In [30] it is shown that the learning cycle of managers' breaks down in complex environments. A reason for this is the time lag between cause and effect.

C: **Increase the use of structured decision making.** Issues 6, 7, 10, 13 and possibly 1 are connected to this group. There is a need for a model or method that can be used to calculate the business value of architectural decisions. The problem is that the customer does not see any value of a new architecture although an architecture can limit for example, to what extent new features can be added. Also decisions in general concerning the E/E system have to be improved. We suggest that a business value model is developed and an increased use of structured decision making. Creating academic models is one thing, but creating models that will work in industry usually something else. We believe that the goal of these models has to be effectiveness and efficiency rather than focusing on optimal decisions. A problem with such model is that it is still hard to value quality attributes against for example cost and time to market. What is the actual benefit by for example achieving flexibility in our system? The models we are seeking is models that can provide some value driven evaluation of quality attributes in the architecture. An attempt to achieve such model is the Cost Benefit Analysis Method (CBAM) [31], but the method does not appear to have gained any significant impact in the automotive industry.

D: **Improve the architecture development process.** This group concerns primarily issue 2, 4, 9 and possibly 14. There are some fundamental processes that are missing. For example there is formally no process for architectural development at any of the companies. The need for new processes has increased as both organizations have grown a lot in the last years. We suggest that a process for architectural development is developed. Complications for improving the architectural process could be the lack of understanding of the E/E system from management on why this is important and hence lack of willingness to contribute resources. This process will most likely include methods for structured decision making as described in Action C and it also describes when in time the organizations will deliver according to their responsibilities (Action A).

E: **Clarify development strategies.** Issue 8 and 12 relate to this group. Today it is unclear how to prioritize between, time, cost and quality. Also the advanced engineering needs to be more separated from actual vehicle projects. We suggest that advanced engineering projects are prioritized and also that the consequences of removing resources and moving advanced engineering projects into vehicle projects too early are clearly shown. A barrier could be that there is a tradition in these companies to prioritize work with earliest deadline first. A possible way to cope with front-loading of projects is suggested in [26].

The only issue that is not included in the suggested actions described above is issue 5. It is not directly connected to the scope of this study and the problem is not directly connected to the E/E system development. However, if the background to this issue is that product planning does not understand how to communicate requirements to the E/E department it could be part of group B.

8.6 Conclusion & Discussion

The complexity of automotive electrical and electronic systems is increasing rapidly. This makes the engineering of these advanced computer-based systems more and more difficult. In particular, finding a good architecture is a prerequisite for successful design.

In this case study we have identified and validated 14 issues that are related to real-world decisions regarding heavy vehiclest' electrical and electronic system architecture. We have shown that these issues are relevant but we cannot say that this is an exclusive set of issues when developing electronic and electrical system architecture. We believe that the method used is well suited for this type of research.

Many of the identified issues are not just technical issues but they also relate to management and organization. The results have been validated by a survey and we can be certain that we have found issues that reflect the situation at the studied OEM. Also we believe that the results are general for the automotive domain. We believe the results of our work is common within the automotive industry because of informal meetings with personnel of our competitors and another study at a different OEM described in [29].

8.6.1 Future Work

To continue the investigation of issues that are related to electrical and electronic system development we will continue with a comparison of issues collected at three different automotive OEMs. It would also be interesting to see how different roles relate to the different issues, i.e. it is most likely that a manager and a programmer will not have the same opinion about what actually is an issue. This study mostly enlightens the problems that exist today, and as a natural next step we will start to sort out how to solve these issues.

8.7 Acknowledgement

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Bibliography

[1] Gariel Leen and Donald Heffernan. Expanding automotive electronic system. In *IEEE Computer*, volume 35, pages 88–93, 2002.

[2] IEEE Recommended Practice for Architectural Description of Software-Intensive Systems. IEEE 1471-2000, 2000.

[3] Goran Mustapic, Anders Wall, Christer Norström, Ivica Crnkovic, Kristian Sandström, Joakim Fröberg, and Johan Andersson. Real world influences on software architecture - interviews with industrial experts. In IEEE, editor, *IEEE Working Conferance on Software Architectures, Oslo, Norway*. IEEE, June 2004.

[4] Stig Larsson, Anders Wall, and Peter Wallin. Assessing the influence on processes when evolving the software architecture. In *IWPSE '07: Ninth international workshop on Principles of software evolution*, pages 59–66, New York, NY, USA, 2007. ACM.

[5] Frank van der Linden, Jan Bosch, Erik Kamsties, Kari Känsälä, and Henk Obbink. Software product family evaluation. *Lecture Notes in Computer Science*, 3154:110–129, 2004.

[6] J. C. Henderson and N. Venkatraman. Strategic alignment: leveraging information technology for transforming organizations. *IBM Syst. J.*, 38(2-3):472–484, 1999.

[7] M.L. Griss. Software reuse architecture, process, and organization for business success. *Computer Systems and Software Engineering, 1997., Proceedings of the Eighth Israeli Conference on*, pages 86–89, Jun 1997.

[8] Rick Kazman, Mark Klein, and Paul Clements. ATAM: Method for architecture evaluation. Technical report, Carnegie Mellon Software Engineering Institute, CMU/SEI-2000-TR-004.

[9] Ola Larses. *Architecting and modeling of automotive embedded systems*. PhD thesis, Royal Institute of Technology, 2005.

[10] Robert S Kaplan and David P Norton. Using the balanced scorecard as a strategic management system. *Harward Business Review*, Jan-Feb 1996.

[11] D.V Steward. The design structure matrix: A method for managing the design of complex systems. *IEEE transactions on engineering management*, 28(3), 1981.

[12] F. Losavio, L. Chirinos, A. Matteo, N. Laevy, and A. Ramdane-Cherif. Iso quality standards for measuring architectures. *The Journal of Systems and Software*, 72(2):209–223, 2004.

[13] *ISO/IEC 9126-1:2001, Software engineering - Product quality*.

[14] Jakob Axelsson. Cost models with explicit uncertainties for elextronic architecture trade-off and risk analysis. In *INCOSE 2006 Annual International Symposium on Systems Engineering*, Orlando, USA, July 2006.

[15] Colin Robson. *Real World Research*. Blackwell publishing, second edition, 2002.

[16] Robert K Yin. *Case Study Research, Design and Methods*. SAGE Publications, Thousands Oak, California, 1986.

[17] Craig J. Russell and Philip Bobko. Moderated regression analysis and likert scales too coarse for comfort. *Journal of Applied Psychology*, 77(3):336–342, June 1992.

[18] Agus Sudjianto and Kevin Otto. Modularization to support multiple brand platforms. In *Proceedings of DETC: ASME Design Engineering Technical Conferences*, Pittsburgh, USA, September 2001.

[19] B. Graaf, M. Lormans, and H. Toetenel. Embedded software engineering: the state of the practice. *IEEE Software*, 20(6):61–69, Nov.-Dec. 2003.

[20] A. Birk, G. Heller, I. John, K. Schmid, T. von der Massen, and K. Muller. Product line engineering, the state of the practice. *IEEE Software*, 20(6):52–60, Nov.-Dec. 2003.

[21] T. Gorschek and C. Wohlin. Identification of improvement issues using a lightweight triangulation approach. *European software process improvement conference (EuroSPI'2003), Verlag der Technischen Universität, Graz, Austria*, pages VI.1–VI.14, 2003.

[22] Dean Tjosvold. Cooperative and Competitive Interdependence: Collaboration Between Departments To Serve Customers. *Group Organization Management*, 13(3):274–289, 1988.

[23] J. Bosch. Product-line Architectures in Industry: A Case Study. *Proceedings of the* 21^{st} *International Conference on Software Engineering, Los Angeles, USA*, pages 544–554, 1999.

[24] John M. Favaro, Kenneth R. Favaro, and Paul F. Favaro. Value based software reuse investment. *Annals of Software Engineering*, 5(1):5–52, January 1998.

[25] Melvin E. Conway. How do committees invent? *Datamation*, april 1968.

[26] Stefan Thomke and Takahiro Fujimoto. The effect of 'front-loading' problem-solving on product development performance. *Journal of Product Innovation Management*, 17(2):128–142, March 2000.

[27] Alan R. Hevner, Rosann W. Collins, and Monica J. Garfield. Product and project challenges in electronic commerce software development. *SIGMIS Database*, 33(4):10–22, 2002.

[28] Claes Wohlin, Per Runeson, Martin Höst, Magnus Ohlsson, Björn Regnell, and Anders Wesslén. *Experimentation in Software Engineering: An Introduction*. Springer, 2000.

[29] Peter Wallin and Jakob Axelsson. A Case Study of Issues Related to Automotive E/E System Architecture Development. In *Proceedings of 15th IEEE International Conference on Computer Based Systems*, pages 87–95, Belfast, Northern Ireland, March 2008. IEEE Computer Society.

[30] Kishore Sengupta, Tarek K. Abdel-Hamid, and Luk N. Van Wassenhove. The experience trap. *Harward Business Review*, 86(2):94–101, February 2008.

[31] Rick Kazman, J Asundi, and Mark Klein. Making architecture design decisions: An economic approach. Technical report, Carnegie Mellon Software Engineering Institute, CMU/SEI-2002-TR-035.

Chapter 9

Paper C: Making Decisions in Integration of Automotive Software and Electronics: A Method Based on ATAM and AHP

Peter Wallin, Joakim Fröberg and Jakob Axelsson
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Abstract

In this paper we present a new method for making decisions on integration strategy for in-vehicle automotive systems. We describe the problem of choosing integration strategy and we describe the method, which is a combination of the Architecture Tradeoff Analysis Method, ATAM, and the Analytical Hierarchy Process, AHP. We exemplify the use of the proposed method by evaluating the integration decisions concerning the physical connection of a realistic example system; a computer controlled automatic gearbox. We present analysis on the use of the method and conclude that the method has several benefits compared to ATAM or AHP used individually. The method firstly supports a structured way of listing system goals, and secondly, it also supports the making of design decisions.

9.1 Introduction

Design of automotive in-vehicle electronic systems is a challenge for Original Equipment Manufacturers, OEMs, due to a large set of functional requirements and stringent quality goals. The system is required to deliver its many functions in a dependable and safe manner, and product costs are to be kept low. The system must fulfil business and life-cycle goals such as being simple to maintain, service, and produce. The resulting system architecture is often complex and system architecture design is a process with many stakeholders. One way of reasoning around architectural choices is to estimate quality attributes of the envisioned system and then try to quantify the impact of different choices.

9.1.1 Integration in Automotive Products

Design of automotive in-vehicle electronic systems includes joining together or integrating functionality developed by several organizations. These sub-systems can be purchased off-the-shelf from a supplier or developed specifically for its purpose by the OEM or the supplier, or a combination of the two. Functionality for sub-systems can be pure software like algorithms or it can be offered with hardware including computer nodes, sensors, actuators, connectors, etc. Integrating an electronic subsystem is the effort of making it conform to the decided architecture. Thus the integration is concerned with finding a design solution so that the component comply with, e.g. diagnostic strategy, system state management and fault handling. More precisely, integration could mean developing glue code or gateway functionality or it could mean to specify to a component supplier the system functionality to which the component must conform.

9.1.2 Problem Description

OEMs often develop architectural guidelines based on the desired qualities and integration solutions should conform to these guidelines. Still integration is difficult. Either guidelines are too rigorous and need to be bent, or guidelines are too vague and fail to aid in design. Integration design, like architecture design, aims at finding a solution that meet many requirements from many stakeholders. This means that the system should not only be designed to provide its main function, but also to meet other requirements. For example, it is desired by the safety team that the system is feasible enough to analyze, and the service people wish for diagnostic functionality to cover all possible faults. Thus, the problem in integration is partly to know the various requirements and their importance, and partly to know what design is best suited.

9.1.3 Our Proposed Method

Our goal is to make the impact of integration decisions visible in terms of the desired properties of the system. Further we want to evaluate different integration strategies to find the one that best support the desired qualities of the product in its life cycle. In order to evaluate success of different integration strategies we need some criteria on how to decide what is favorable.

The approach of this work is to use scenarios from the Architecture Tradeoff Analysis Method, ATAM [1], and analyze them with the Analytical Hierarchy Process ,AHP [2], to evaluate different integration strategies in the context of an automotive electronic system. Major research exists on both ATAM and AHP and both methods are quite commonly used [3, 4, 5].

The contribution of this work is the proposed method that combines ATAM and AHP, enabling structured reasoning and decision making. Although both methods are commonly used, still, there is to our knowledge no suggestion on how the two methods may be combined even if the possibility is mentioned by [6]. The method is applied to and intended for the context of automotive software and electronic systems, and more specifically we apply it to the decision making in choosing integration strategies. Although this paper focus on a limited number of integration strategies we believe that it can be used for all kind of integration strategies as well as other architectural decisions.

To demonstrate our approach we use an example concerning integration of a gearbox for construction equipment vehicles such as haulers, wheel loaders, and excavators. The example is simplified but has realistic specifications.

The rest of the paper is organized as follows. Section 2 introduces vehicle electronic systems. The properties of a vehicle electronic system is outlined in Section 2.1 and the four different integration strategies are presented in Section 2.2. We introduce a gearbox example in Section 2.3. Section 3 describes the proposed method. In Section 4 we provide a theoretical but realistic example of how the method will work. In Section 5 we analyze the method. Section 6 concludes the paper.

9.2 Vehicle Electronic Systems

In this section we present the context of automotive in-vehicle electronic systems. Further, we describe the notion of integration strategies and we provide a theoretic example of an automotive electronic system intended for integration based on previous studies.

9.2.1 General Properties

Automotive electronic systems are safety critical, real time systems embedded in mechatronic components. The functions in an automotive vehicle include control of the engine and drive train, driver interface, suspension, comfort functions such as climate control, and audio/video systems. Besides the user functionality of the vehicle, there are numerous functions inside a vehicle that supports the production and service operations in the lifecycle of the product such as diagnostics and test. Sometimes the system and functionality is described as partitioned into subdomains, such as, powertrain, body, chassis, and infotainment. The implementation of the functionality in contemporary vehicles includes distributed computers with I/O to sensors and actuators. Wiring is substantial and bundled in cable harnesses. Control software is often constructed using a dataflow model and communication is often based on the CAN protocol.

In-vehicle computer systems are often labeled electronic systems in automotive applications. Automotive electronics thus includes electronic hardware such as sensors, actuators, Electronic Control Units (ECUs), and wiring, but also the software. The reason for using this term may be the close dependency of software and hardware in many automotive applications. For instance, a braking application is very tightly bound to the hardware for which it is tested and developed. A change of sensors or other hardware components in such an application would likely generate a change of software functionality. In the following we use the term electronic system to refer to the complete in-vehicle computer system including both software and hardware.

9.2.2 Integration Strategies

Integration of new functionality is an iterative process. New functionality is added to an existing platform during many years. The same platform is also used for many different models and even different products.

Decisions on integration strategy will affect the quality outcome and lifecycle cost of not only the electronic system, but the complete vehicle. Integrating supplier electronics in automotive networks is challenging because several qualities are pursued simultaneously, much like in architecture design.

An integration strategy provides answers to questions on how a component will be made to fit into system wide schemes and principles. It is the design of interfaces and semantics of interaction between component and system. There may be several schemes to follow such as diagnostic signaling, fault handling, and state management. The component and its function can give rise to ways of interacting that are not covered by the decided system principles and schemes. An example is a mechatronic brake with many fault states that each affect the system state differently. Such issues are included in the integration strategy.

Network topology decisions is part of the integration strategy. To describe the method of evaluating integration strategies we focus on how a function is to interface the system. The four alternatives we consider in this paper are shown in Figure 9.1 and are explained in the list below.

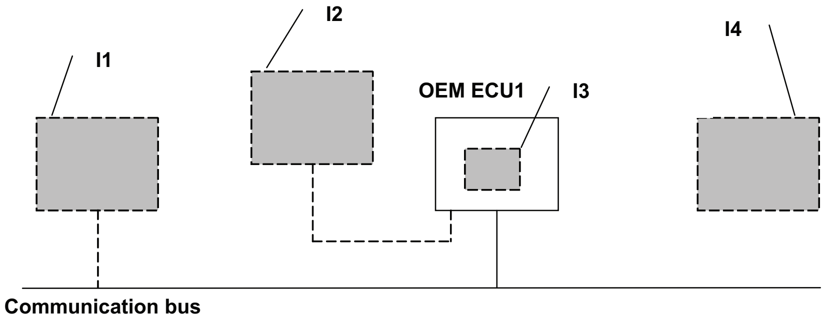

Figure 9.1: **Four choices in integration strategy**

I1. New ECU connected directly on a system bus.

I2. New ECU connected via a gateway.

I3. Application software component located in existing ECU.

I4. New ECU stand alone - not connected to a bus.

9.2.3 Example: Gearbox

Thus, new ECUs contains both a new software functionality and a software environment including operating system, device drivers, and possibly more. Integration strategy I3 on the other hand involves only the software function without surrounding infrastructure. Based on a previous study of three cases of real-life mechatronic integration [7], we have developed a theoretical but realistic example of a component intended for integration in an automotive application. The example consists of a mechanical gearbox with a fitted ECU that controls the operation of the automatic gear shifting intended for use in a construction equipment vehicle.
The ECU is equipped with the following interfaces:

- A CAN interface
- J1939 [8]
- A serial interface with a proprietary protocol for diagnostics

The gearbox application is dependent on signals that describe the gear lever position, engine speed, vehicle speed, and drive mode. The application must be able to control engine speed for short periods of time during gearshifting. There are timing requirements on the control messages; latency, periodicity, and jitter are specified. The application also has a number of error states where gearshifting is not possible.

9.3 The Method Explained

ATAM is a method for identifying important design decisions and show how they tradeoff against each other in software architectures. AHP is a multi criteria analysis method. By combining the two methods we can use scenarios produced by ATAM as input to AHP and carry out a robust evaluation of both scenarios and how well an integration strategy fits a certain scenario. In this section, we briefly summarize the original methods and theen comment on how we combine them for decision support in an automotive Electrical/Electronic architecture.

9.3.1 ATAM

The goal of ATAM is to assess the consequences of architectural decisions in the light of quality attribute requirements [1]. Typically there exist competing quality attributes such as modifiability, security, reliability and maintainability that different stakeholders consider to be the most important. These quality attributes are broken down into scenarios. ATAM is divided into nine steps. These steps involve eliciting a utility tree and identifying risks, sensitivity and tradeoff points.

In our approach we only consider some of the steps in ATAM and it is mostly how the scenarios in the utility tree are generated that is of relevance in the proposed method. The complete description on ATAM can be found in [1].

9.3.2 AHP

The Analytic Hierarchy Process (AHP) is a multi-criteria decision making approach in which factors are arranged in a hierarchic structure [2]. In AHP all element are compared against each other which yield a robust result but also time consuming due to the large number of comparisons. Elements are compared according to Table 9.1. In this paper we use an AHP related approach called Chainwise Paired Comparison (CPC) [9]. CPC only requires the same amount of comparisons as the number of elements. However the consistency needs to be validated to ensure the same result as with AHP. The CPC algorithm is shown in Table 9.2 which is adapted from Table 1 in [9].

Table 9.1: Element comparison

Scale	**Importance**
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2,4,6	Intermediate values

We are interested in for n elements finding the weight W_i. Since it is difficult to estimate this weight directly, we instead ask the decision maker for the ratio R_i between two successive elements as shown in Equation 9.1.

$$R_i = \begin{cases} \dfrac{W_i}{W_{i+1}} & : i = 1..n-1 \\ \dfrac{W_n}{W_1} & : i = n \end{cases} \tag{9.1}$$

Table 9.2: **Algorithms used in chainwise paired comparison**

i	R_i	D_i	$\tilde{R}_i$	M_i	V_i
1	$\frac{W_1}{W_2}$	D_1	$\frac{D_1}{\sqrt[n]{\prod D_j}}$	$\tilde{R}_1 \cdot M_2$	$\frac{M_1}{\sum M_j}$
2	$\frac{W_2}{W_3}$	D_2	$\frac{D_2}{\sqrt[n]{\prod D_j}}$	$\tilde{R}_2 \cdot M_3$	$\frac{M_2}{\sum M_j}$
:	:	:	:	:	:
n-1	$\frac{W_{n-1}}{W_n}$	D_{n-1}	$\frac{D_{n-1}}{\sqrt[n]{\prod D_j}}$	$\tilde{R}_{n-1} \cdot M_n$	$\frac{M_{n-1}}{\sum M_j}$
n	$\frac{W_n}{W_1}$	D_n	$\frac{D_n}{\sqrt[n]{\prod D_j}}$	1	$\frac{M_n}{\sum M_j}$

D_i represents the estimated value of the ratio R_i. If the estimate is perfect then Equation 9.2 is true, meaning that the estimates are consistent.

$$\prod_{j=1}^{n} D_j = 1 \tag{9.2}$$

Full consistency can be hard to achieve in practice with many factors to chainwise compare. To compensate for this inconsistency we compute a new estimated ratio, $\tilde{R}_i$, with Equation 9.3. $\tilde{R}_i$ is by definition a consistent estimation, fulfilling Equation 9.2.

$$\tilde{R}_i = \frac{D_i}{\sqrt[n]{\prod\limits_{j=1}^{n} D_j}} \tag{9.3}$$

Assume that M_i represent W_i/W_n and since $\tilde{R}_i$ is an estimate of R_i, M_i can now be computed recursively with equation 9.4.

$$\begin{cases} M_i = \tilde{R}_i \cdot M_{i+1} \\ M_n = 1 \end{cases} \tag{9.4}$$

We now have a weighted list of elements. To make values comparable to each other we normalize the weights with Equation 9.5.

$$V_i = \frac{M_i}{\sum\limits_{j=1}^{n} M_j} \tag{9.5}$$

9.3.3 The Proposed Method

We have devised a method, based on a combination of ATAM and AHP, that allow us to find the best choice out of a number of possible designs. The basic steps in the method are shown below, and later exemplified with more details in the next section.

1. Elicit scenarios from system stakeholders
2. Rate importance of scenarios
3. Assess scenario fulfilment of each design choice

Elicit scenarios from system stakeholders. Using some of the basic steps of ATAM, a list of scenarios is extracted. Each scenario represents an important aspect of the system that is desired in order to achieve a "good" system. What constitutes a good system depends on who you ask, and therefore, the ATAM stipulates to involve many stakeholders that has interests in the systems life cycle as well as experienced system architects. The scenarios that come from this elicitation can be grouped in a tree structure called a utility tree, and in this way the scenarios can be shown to belong to a certain quality attribute such as reliability. This work involves interviews and workshops and can be substantial. However, the resulting set of scenarios is a general characterization of the system requirements in terms of qualities. Thus, it is not only usable for a particular decision. As the life cycle of an automotive product is different for different companies, it seems unrealistic to elicit a general utility tree even for a certain kind of vehicle. The generality of the scenarios is likely confined to the company and possibly to the type of vehicle, e.g., a minivan or sports car. The ATAM stipulates a procedure for prioritizing scenarios and this can be used to shorten the possibly long list of scenarios.

Rate importance of scenarios. A more formal prioritization and weighting of scenarios can be made by employing the AHP procedure. Comparing each scenario to all others to get a weighting is possible and the most accurate method for AHP prioritization. Since the number of comparisons required with

AHP are $n(n-1)/2$ we get, even with a small set of scenarios an extensive list of comparisons. We instead propose to use chainwise paired comparison as shown in [9], to reduce the number of comparisons to n. Chainwise comparison is made by comparing the first scenario with the following in the list. This is continued for all scenarios and finally the last scenario is compared to the first to get a "chain". Each comparison is made using the AHP method scores that are shown in Table 9.1. This procedure yields a weight for each scenario that corresponds to the importance of that scenario.

Assess scenario fulfilment of each design choice. Here, we have to have a number of defined design choices. For each design choice, a fulfilment is estimated of each scenario i.e. it should be estimated how well each design choice meets each scenario. For instance a simple design may score high on a scenario requesting ease of safety analysis. More in detail, each design decision is compared to another in chainwise manner until all have been visited and the last compared to the first. What this gives us, after AHP prescribed calculations, is a weight for each design decision. The weight corresponds to how well that design meets the selected scenario. So, for a set of four defined design alternatives and 16 scenarios, we get a sum of $4 * 16$ weights. The final step in finding the best solution is then calculated by using the weight (importance) of each scenario. Now, we know the "goodness" of the design choice with respect to each scenario, and we also know the importance of each scenario. We add up the product of scenario weight and design choice weight for all scenarios. This number corresponds to how much fulfilment of all the scenarios that this particular design decision has, and thus we have comparable numbers for the set of design decisions. This final step is not general, but the estimations of fulfilment must be made for a certain automotive product, for a certain component to be integrated.

9.4 Using the Method

In this section we explain how the method can be used. The gearbox from the example in Section 9.2.3 is to be integrated with one of the four different integration strategies explained in Section 9.2.2.

The ATAM proposes that this elicitation is done in two workshops including all key personnel. For practical reasons, we have deviated from the stipulated workshop format and elicited a utility tree based on four interview sessions with only two experts individually. First we use interview results from previous work on quality attributes in automotive electronics and software systems [10][11]. We use these results to construct an initial utility tree which is then used to guide another round of interviews. This round yields a set of scenarios that we use in our following theoretical example.

9.4.1 Scenarios

ATAM states that "A scenario is a short statement describing an interaction of one of the stakeholders with the system". Here we list the scenarios that we elicited from the interviews with architects and product specialists. The respondents described the business situation related to each quality attribute. This list is not at all a complete list of scenarios that should be considered but for explaining the method we find it sufficient. In order to extract a complete list, we would like to include all stakeholders and also fully utilize the workshop format proposed in ATAM.

Below is the list of scenarios that where elicited from the interviews categorized under their main utility.

Safety

S1. A safety related function experiences a fault and this does not lead to an unsafe state of the system

S2. The system experiences a fault and each safety related function can reduce functionality according to a system wide policy

S3. Each safety related function does not add any non recoverable unsafe states (e.g. loss of steering is difficult to recover safely from)

S4. Safety analysis is performed and the logics of each safety related function is visible for inspection

Reliability

S5. Overall reliability benefits from certified or tested physical criteria - EMC, moist, dust, vibration and shock

S6. A fault occurs and fault tolerant design upholds system function

S7. Minimum number of connectors wanted

S8. Testable design wanted

S9. Simpleness preferred

S10. Fault diagnosis desired

Modifiability

S11. A function is to be reused in a new vehicle project and the system functionality partitioning is different

S12. A function is to be reused in a new vehicle project and different networks and protocols are to be used

S13. Porting SW platform to new hardware

Serviceability

S14. A function is faulty and the on-board diagnostic system finds the root case of the problem (e.g. eroded connector or faulty sensor)

S15. Physical components are easily replaced

S16. Software functionality is easily replaced

9.4.2 Prioritizing the Scenarios with Chainwise Paired Comparison

Here the 16 scenarios are prioritized with CPC. In this example we assume that the 16 scenarios elicited from the interviews are the most important ones. Asking the full set of stakeholders the number of scenarios could have been significantly larger. The lowest prioritized scenarios would then be discarded as not important enough to affect the choice of integration strategy. In Table 9.3 the scenarios are chainwised compared. It is only the value D_i that is manually estimated according to Table 9.1 in Section 9.3.2. All other values are calculated with the equations in Table 9.2. V_i is the calculated priority. In this theoretical gearbox example S_3 is considered to be the most important scenario and will therefore have higher impact when integration strategy is chosen.

As explained in Section 9.3.2 we need to check if the system is consistent. In this example the consistency is calculated to 98%. Table 3 in [9] shows that for 16 elements the consistency needs to be at least 95.7% for the data to be valid.

Table 9.3: **Scenarios prioritized with chainwise paired comparison**

i	R_i	D_i	I_i	$\tilde{R}_i$	M_i	V_i
1	S_1/S_2	2	2,915	2,048	3,907	0,090
2	S_2/S_3	$\frac{1}{5}$	0,292	0,205	1,908	0,044
3	S_3/S_4	1	1,458	1,024	9,318	0,213
4	S_4/S_5	7	10,204	7,167	9,101	0,208
5	S_5/S_6	$\frac{2}{5}$	0,583	0,410	1,270	0,029
6	S_6/S_7	7	10,204	7,167	3,101	0,071
7	S_7/S_8	$\frac{1}{3}$	0,486	0,341	0,433	0,010
8	S_8/S_9	$\frac{1}{3}$	0,486	0,341	1,268	0,029
9	S_9/S_{10}	1	1,458	1,024	3,715	0,085
10	S_{10}/S_{11}	2	2,915	2,048	3,628	0,083
11	S_{11}/S_{12}	3	4,373	3,072	1,772	0,041
12	S_{12}/S_{13}	1	1,458	1,024	0,577	0,013
13	S_{13}/S_{14}	$\frac{2}{7}$	0,437	0,307	0,563	0,013
14	S_{14}/S_{15}	7	10,204	7,167	1,834	0,042
15	S_{15}/S_{16}	$\frac{1}{4}$	0,364	0,256	0,256	0,006
16	S_{16}/S_1	$\frac{1}{4}$	0,125	0,239	1,000	0,023

Table 9.4: **Scenario S8**

i	R_i	D_i	I_i	$\tilde{R}_i$	M_i	V_i
1	I_1/I_2	2	2,400	2,093	2,866	0,274
2	I_2/I_3	$\frac{1}{4}$	0,300	0,262	1,369	0,131
3	I_3/I_4	5	6,000	5,233	5,233	0,500
4	I_4/I_1	$\frac{1}{3}$	0,400	0,349	1,000	0,096

9.4.3 Weighting Scenarios Against an Integration Strategy

Each scenario is now weighted against the four different integration strategies. After this comparison we have a prioritized list of all scenarios and also one list per scenario showing how well each integration strategy meets the particular scenario. Displayed in Table 9.4 is how well scenario S_8 correspond to each of the four integration strategies. The final analysis is done by using the weight V_i of each scenario and multiply it with the weight of how well it is supported by each integration strategy. This is shown in Table 9.5. The integration that seems to be most suitable in the gearbox example is integration strategy I_3.

Table 9.5: **Decision matrix**

		I_1	I_2	I_3	I_4
S_1	0,090	0,077	0,154	0,077	0,692
S_2	0,044	0,321	0,321	0,321	0,036
S_3	0,213	0,370	0,185	0,370	0,074
S_4	0,208	0,067	0,081	0,686	0,166
S_5	0,029	0,125	0,125	0,625	0,125
S_6	0,071	0,286	0,143	0,429	0,143
S_7	0,010	0,227	0,160	0,453	0,160
S_8	0,029	0,274	0,131	0,500	0,096
S_9	0,085	0,273	0,154	0,086	0,486
S_{10}	0,083	0,364	0,182	0,364	0,091
S_{11}	0,041	0,125	0,125	0,625	0,125
S_{12}	0,013	0,127	0,301	0,537	0,035
S_{13}	0,013	0,113	0,126	0,556	0,205
S_{14}	0,042	0,286	0,143	0,286	0,286
S_{15}	0,006	0,222	0,222	0,111	0,444
S_{16}	0,023	0,174	0,162	0,602	0,062
Final priority		**0,227**	**0,153**	**0,414**	**0,205**

9.5 Analysis

The goal of this work is to find a feasible method that can be used in practical cases of decision making in the context of integration of automotive electronics.

9.5.1 The Method Compared to AHP and ATAM

The method does provide a structured way of using expert knowledge to make decisions in design of automotive electronics and possibly many other areas. Like ATAM recognizes, the difficulties in making decisions stems from the complexity where many stakeholders have different goals. What ATAM lacks is the actual support for decision making. ATAM is instead intended to identify sensitive design points in the system, but choosing a design alternative must be done by other means. AHP on the other hand is a method for decision making with multiple criteria, but lacks a structured way of listing the criteria. Thus, using the concept of scenarios and utility trees from ATAM as input to an AHP process gives us a method that includes both benefits. Compared to using ATAM alone, the combined method supports decision making and should still have the benefits that has been reported with ATAM. One such important benefit is that stakeholders get to reason about qualities and their fulfilment. Thus, compared to using AHP alone, we will get both a structure for the criteria and likely also the benefit of stakeholder involvement and communication.

9.5.2 Methods Pros and Cons

One of the main problems with multi criteria decisions is to find out the relative importance of each goal. To investigate this, a number of estimates must be made by experts. It is much desired to keep the number of estimations low to get a feasible method. The AHP method prescribes comparing and estimating the relative importance of each criteria against all other, and thus having a matrix of estimations to perform with $n(n-1)/2$ estimations. For weighting the importance of the scenarios, we chose to perform chainwise paired comparison that reduces the number of comparisons to n. It should be noted though that the weighting of scenarios is something that can be reused for other decisions. A large effort in weighting scenarios could be accepted if there are many decisions to make.

- **Flexible and scalable**. As we progress through the method we can choose to employ more or less rigorous comparisons depending on the importance of the design decision. For instance it may be justified to employ the full comparison scheme as opposed to the chainwise, if we would want to integrate a new engine system with high impact on system behaviour. Likewise we can choose to have a high number of scenarios if the decision is judged very important.

- **Feedback on accuracy**. The AHP calculations produce a measure of consistency for the estimations made by the experts. Thus, both in the second and third step we will get feedback on whether the interviews have been successful. If the consistency is too low, we can instead decide to redo some of the importance assessments.

- **The method has some support for answering why**. An important issue when designing systems is to have an understanding by all involved why a certain design has been chosen. If the "why" is clearly understood, we run a low risk that the decision is overrun by a new decision. It is clearly visible in the AHP process how the relative importance measures have been estimated. This would likely aid in the effort of explaining why decisions have been made.

9.6 Conclusions

In this paper, we have presented a new method for making decisions on integration strategy for in-vehicle automotive systems. The method is based on a combination of the Architecture Tradeoff Analysis Method, ATAM, and the Analytical Hierarchy Process, AHP. We have described the method in detail and exemplified its use with a theoretical but realistic example of an electronic controlled gearbox that is to be integrated into an in-vehicle electronic system. Analyzing the method and the example, we have shown that the method is usable and has benefits compared to either ATAM or AHP used individually. Like ATAM, this method provides a way for stakeholders to reason about system qualities, but it does not stop at identifying important design points. Compared to using ATAM alone, our combined method supports decision making and should still have the benefits that has been reported with ATAM. One such important benefit is that stakeholders get to reason about qualities and their fulfilment. Thus, compared to using AHP alone, we will get both a structure for the criteria and likely also the benefit of stakeholder involvement and communication.

In analyzing the method and the example, we have also shown that the method seems feasible and that it supports some desired properties. Firstly, it is scalable in effort to compensate for more or less crucial decisions. Secondly, we show that it provides feedback on the quality of the estimates. Thirdly, the method does provide some documentation as to why a decision has been made and this possibly helps in understanding and communicating system design among stakeholders.

Bibliography

[1] Rick Kazman, Mark Klein, and Paul Clements. ATAM: Method for architecture evaluation. Technical report, Carnegie Mellon Software Engineering Institute, CMU/SEI-2000-TR-004.

[2] T.L Saaty. *The analytic hierarchy process*. New York: McGraw-Hill, 1980.

[3] Mario Barbacci, Paul Clements, Anthony Lattanze, Linda Northrop, and William Wood. Using the architecture tradeoff analysis method (ATAM) to evaluate the software architecture for a product line of avionics systems: A case study. Technical note, CMU/SEI-2003-TN-012, 2003.

[4] John K. Bergey and Matthew J. Fisher. Use of the architecture tradeoff analysis method (ATAM) in the acquisition of software-intensive systems. Tecnical note, CMU/SEI-2001-TN-009, 2001.

[5] G C Roper-Lowe and J A Sharp. The analytic hierarchy process and its application to an information technology decision. *The Journal of the Operational Research Society*, 41(1):49–59, jan 1990.

[6] Liming Zhu, Aybke Aurum, Ian Gorton, and Ross Jeffery. Tradeoff and sensitivity analysis in software architecture evaluation using analytic hierarchy process. *Software Quality Control*, 13(4):357–375, 2005.

[7] Joakim Fröberg and Mikael Åkerholm. Integration of electronic components in heavy vehicles: A study of integration in three cases. In *Proceedings from Systems Engineering/Test and Evaluation Conference, Melbourne, 25-27 September 2006*, Melbourne, September 2006.

[8] SAE J1939 Standard - The Society of Automotive Engineers (SAE) Truck and Bus Control and Communications

Subcommittee, SAE J1939 Standards Collection, 2004 Available at: http://www.sae.org/products/j1939.htm.

[9] Jang W Ra. Chainwise paired comparison. *Decision Sciences*, 30(2):581–599, 1999.

[10] Anders Möller, Mikael Åkerholm, Joakim Fröberg, and Mikael Nolin. Industrial grading of quality requirements for automotive software component technologies. In *Embedded Real-Time Systems Implementation Workshop in conjunction with the 26th IEEE International Real-Time Systems Symposium*, 2005 Miami, USA, December 2005.

[11] Anders Möller, Joakim Fröberg, and Mikael Nolin. Industrial requirements on component technologies for embedded systems. In *International Symposium on Component-based Software Engineering (CBSE7)*, Edinburgh, Scotland, May 2004. Springer Verlag.