Architecting Complex Embedded Systems: An Industrial Case Study

Håkan Gustavsson
Mälardalen University
Västerås, Sweden
hakan.gustavsson@mdh.se

Jakob Axelsson
Mälardalen University
Västerås, Sweden
jakob.axelsson@mdh.se

Abstract— ***This paper studies the current state of architecting practices in three different industrial segments which are characterized by being software-intensive. The context of the six different companies as well as the architecting practices are compared and analyzed. The methods used to solve the tasks within the architecting process are mapped to the context where it has been used in industry. An analysis of the case study indicates how different methods are more suitable in different environments. Many of the successful practices found in the study can be explained by external factors related to the context of the different companies. Others relate to the internal structure of the organization, including its maturity which is measured by assessment through an adaption of the Capability Maturity Model Integration (CMMI).***

Keywords—Design methodology; Case study; Architecture; Embedded systems; Maturity.

I. INTRODUCTION

Many traditionally mechanical companies in industries such as automotive, telecommunication, process automation, and defense are becoming more software-intensive and now constitute systems of systems. The rapid increase of new functionality implemented through software enhances the burden of the architecture to enable future growth of the system. The architecture of those software-intensive systems describes its building blocks and their relationships to each other and to the environment [9].

As we see it, the architecting process is central to and dependent on many factors within the organization. The architects are constantly forced to make decisions on opposing factors such as continuous evolution versus product stability [17]. To stay competitive, companies need to adapt their processes to include the new discipline of software engineering.

This paper investigates how architecting is performed in different companies. Our underlying informal hypothesis was that a number of *external* factors related to the company, the industry, and the market influence what practices are used, together with *internal* factors such as the process maturity and organization of development.

The study was made on companies developing embedded systems including both hardware and software. These systems are mechatronic which adds complexity since many issues cross several engineering disciplines. The systems are resource constrained and trade-offs between the system behavior and the resources required are of great importance. Both hardware and software are mixtures of in-house development and deliverables from external suppliers. The systems are distributed on different hardware platforms and are sold in a large number of variants.

The rest of the paper is organized as follows. In the next section, related work is presented. In Section III, an overview of the research method used is presented. In Section IV, we discuss how maturity can be assessed, which is one of the internal factors that we have studied. In Section V, the companies participating in the study are presented, and in the following section, the findings are presented. The findings are further analyzed in Section VII, and the final section presents conclusions and ideas for future research.

II. RELATED WORK

There are many methods and tools available to aid the architects in their work, but far from all are commonly used in practice. Examples of structured methods mentioned in industry surveys [1] are Pugh evaluation matrix [16] and the analytical hierarchy process (AHP) [19]. In a study of 46 companies made 2005 in Finland [20] it was shown that the most common (76%) used concept selection method was concept review meetings, and similar results were shown in [7].

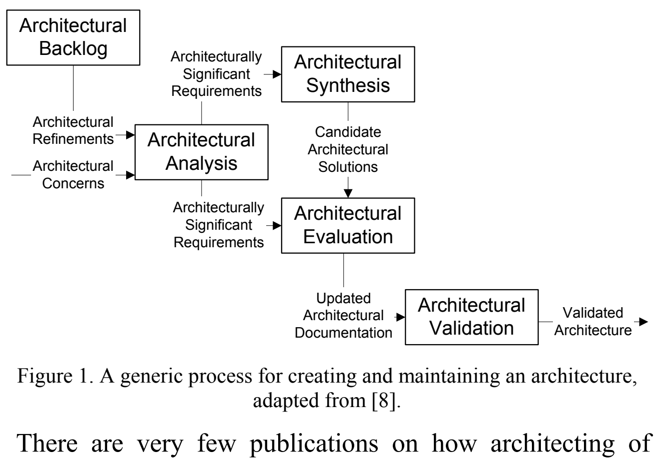

Figure 1. A generic process for creating and maintaining an architecture, adapted from [8].

There are very few publications on how architecting of software-intensive systems is done in practice. Decisions in the development process [7] and within the architecting process [15] have been previously studied and this provided us with ideas for what factors to include in our study.

Axelsson et al. [2] compare network architectures of three different automotive manufacturers and conclude that business and product characteristics have a large impact on the network architecture, which motivates our hypothesis.

The architecting process involves many stakeholders who all produce knowledge needed to develop the architecture. Liang et al. [12] present a process based on architectural knowledge for software architecting. Architecting of software systems are described in many pieces of literature. For example, Eeles [5] presents the process of software architecting of IT system. Most available architecting processes are software oriented, with the architecting method CAFCR [14] being one exception. It has a focus on what the internal and external customer wants on a system level of embedded systems.

Through comparison of available processes Hofmeister et al. [8] have developed a generic process for creating and maintaining an architecture. Inspired by Scrum [21] the process (Figure 1) emphasizes the need of a backlog to keep track of issues found in the architecture.

When it comes to evolutionary architecting, one of the papers in the area is a case study describing how change requests to the architecture is handled in an automotive company [3]. It provides valuable information on the nature of the evolutionary process and its relation to revolutionary architecting.

III. Method

Different companies perform architecting in various ways and there are many different factors that influence. Many of those factors are thought to be soft factors [6] that are hard to find through, for example, a questionnaire. In order to understand the context in which different methods are being used, personal interviews was found to be the most appropriate method.

The case study was performed in eight steps:

1. The questions were developed and tested on people with similar roles, who were not included in the study.
2. Companies were chosen and a connection was established through a contact person. In collaboration with the contact person the architects were identified.
3. At least two interviews were held with architects at each company.
4. The current results of the study were presented to a broader audience at each company visited. During the presentation the situation at the visited company was also discussed.
5. Questions about the characteristics of each company were answered by the contact person.
6. The results were gathered in a database and analyzed.
7. The results were also reviewed by the contact person at each participating company.
8. A comparison was made with the interview data and data previously collected on the process maturity of a few of the companies.

The professional network of the authors was in many cases used to establish connections with the right persons and at one company the respondents were previously known to the interviewer.

The chosen format of the interview was semi-structured and the answers were audio recorded. A semi-structured interview has predetermined questions, but the order can be modified based upon the interviewer's perception of what seems most appropriate. Question wording can be changed and explanations given [18]. The interviews at all companies followed the same template and the answers given were then used to compare the companies.

To be able to compare the companies, a number of metrics were used that are presented in Table I. Some of these metrics are external, referring to characteristics of the market or industry that the company is part of, and others are internal, relating to how development is organized. Every company and organization is different in many ways, and they may use different definitions of these metrics. We choose to use each company's own definition, rather than to enforce a common definition, since this increased the likelihood of getting good responses. The values have been given by asking, for instance, how many employees are working within the company's R&D organization. The answers will not be exactly comparable since R&D is not the same in all companies, e.g. supporting units are sometimes included or not. Even if the organizations would be the same, different companies count people differently, e.g. with or without consultants. The goal of the metrics is to give an overall picture of the different companies and that goal is thought to be fulfilled even if the definitions of the metrics are not exact.

The last step in the process was intended as a triangulation [18], i.e. to improve validity by adding a secondary source of information. The method used is presented in the next section. (The actual collection of maturity data was done in a previous study with a subset of the companies, which explains why this information is missing for some of them.)

IV. Evolutionary Architecting Maturity Model

In this section, we briefly describe the levels of the Evolutionary Architecting Maturity Model (EAMM) [4]. The model is derived from the Capability Maturity Model Integration (CMMI), but is greatly simplified and tailored for assessing architecting organizations. Since these teams are usually fairly small (e.g., no more than 10 persons in our study), it was designed to be light-weight, allowing appraisals in a few hours based on a questionnaire with 53 questions which are answered on a five-grade scale. The answers are weighed together to form a maturity score between 0 and 5 that indicates the level of the company.

Level 0: Incomplete

In the EAMM, we have included a Level 0. A company at this level does not work with product lines at all, but each product has its own architecture and the ambition for reuse is low.

Table 1. A comparison of the characteristics of the studied companies (all values are approximations).

	Context \ Company	Automotive 1	Automotive 2	Automotive 3	Defense 1	Industrial Automation 1	Industrial Automation 2
Internal	**Size of R&D organization**	Large	Very large	Large	Medium	Small	Small
Internal	**Relative size of the embedded systems organization in comparison to total R&D**	20%	13%	8%	18%	67%	24%
Internal	**Number of architects**	6	10	4	3+6	3+4	0-5
Internal	**Management levels between architects and CEO**	5	6	4	4	**2 and 4**	3
Internal	**Maturity level according to EAMM**	**3.17**	1.57	1.39	-	-	-
Internal	**The power center of the organization**	Line	Project	Project	Line	Project/Line	Project
Internal	**Geographical locations of R&D organization**	1	1	**~10**	1	2	3
Internal	**In-house system development**	50%	10%	80%	50%	**95%**	**90%**
External	**Product variants**	Very high	High	Very high	**Low**	Medium	Medium
External	**Main customer**	Business (small/large)	Private	Business (small/large)	Government	Business (large)	Business (small/large)
External	**Magnitude of the investment for the customer**	Medium/High	Very high	Medium/High	Small	Small	Medium/High

There is no organizational responsibility for architecture across the products, and no defined process.

Level 1: Initial

A company who fulfills the requirements that it is working evolutionary based on product lines and has an organization responsible for architecting the products is at least at EAMM Level 1. At this initial level, the processes are usually ad hoc and chaotic, and success is highly dependent on the skills of the people.

Level 2: Managed

At EAMM Level 2, an organizational policy is established where the roles and responsibilities of the architects are formalized with respect to other parts of the development organization. There is a need at this level to define what quality attributes should serve as guiding principles for the architects' work. These should not be connected to any specific function, and should relate primarily to the product line architecture rather than to the architecture of individual products.

Level 3: Defined

At EAMM Level 3, processes are institutionalized in the organization, and they are improved over time and adapted for each architectural change request through tailoring guidelines. EAMM defines 11 process areas at this level, which are the same as in CMMI.

Level 4: Quantitatively Managed

At EAMM level 4, the organization uses quantitative analyses to establish a stable architecting process with predictable behavior.

The organization has defined what metrics it should use to measure the process performance of its architecting processes. Based on the metrics it measures the progress of individual CRs to collect statistical data about the various sub-processes. The organization puts up objectives and takes corrective actions if these are not satisfied. Statistical methods are applied on the collected data to identify causes of variation, with focus on special causes (rare events) that need to be removed in order to reach a stable process performance.

Level 5: Optimizing

At EAMM level 5, the organization continually improves its processes and architectural assets based on a quantitative understanding of the common causes of variation. It also strategically manages the architecture by identifying future bottlenecks and planning for refactoring at suitable times. To achieve this, the organization needs to identify which the limiting factors are in the architecture.

V. CASE COMPANIES

The studied companies are common in many ways. They are all financially successful and all have a very long Swedish history. They are also internationally well-known and considered premium brands within their business segments. The products are all complex software systems with a long life-cycle (15-30 years) that may include multiple owners. In the following sections the characteristics of each company will be presented. The comparison is summarized in Table 1 and some clarifications of the measures are given below:

- The size of the R&D organizations and the number of product variants is relative in comparison to the other case companies.
- The relative size of the embedded systems organization is in comparison to the total number of employees within R&D.

- The measure “number of architects” shows how many architects that are working on a complete embedded system level.
- The power centre of the organization describes if the architects consider the organizations to be project-oriented or line-oriented.
- The magnitude of the investment for the customer indicates the size of investment relative to the economy of the most common customer.
- The total EAMM level is an approximate maturity level of the organization.

A. *Automotive 1 (A-1)*

This company produces commercial vehicles. The customers of the vehicles are both small and large companies. The product can be configured in a very high number of product variants. This is done using a common product line architecture that supports all different variants. The company has its R&D centralized to one location and has for a long time applied the thoughts of Lean [13] onto its development.

B. *Automotive 2 (A-2)*

This company is a car producer. The customers of the vehicles are mostly individuals and in some cases companies. This makes the magnitude of the investment for the customer often very high. The company has the largest R&D organization of the companies included in the study and its R&D is centralized to one location. The relative size of the electronic and electric system development organization is 13 percent, which is explained by a low degree of in-house development. The architecting is divided into two groups responsible of traditional electrical systems and software-intensive systems.

C. *Automotive 3 (A-3)*

This is another producer of commercial vehicles. The company has R&D located at more than 10 different locations worldwide. As with A-1 the product can be configured in a very high number of product variants. The different product lines use the same software and hardware architecture on most in-house developed subsystems, but the interface between subsystems are not standardized between the different product lines.

D. *Defense 1 (D-1)*

As with most companies in the defense industry, the main customers are governments in different countries. The product variants are in comparison low. Customers usually purchase a unique variant of an existing product. The customer requirements are often detailed and may include demands on using a specific supplier of subsystems. The company has its R&D centralized to one location. There are three architects working on the complete system and six who work only with embedded systems.

E. *Industrial Automation 1 (I-1)*

The customer is mostly large companies. The development is mainly in Sweden, but some development is also done in Asia. The relative size of the electronic and electric system development organization is 67 percent, which is explained by a high degree of in-house development. The system is often integrated into a larger system. There are three architects working on the complete system and four who work only with embedded systems.

F. *Industrial Automation 2 (I-2)*

The customer of the systems is both small and large companies. As with I-1 the development is mainly in Sweden, but some development is also done in Asia and the US. The system is usually a major investment for the customer. The electronic and electric system development organization is the smallest of the companies included in the study.

VI. CASE STUDY FINDINGS

Architects at all companies mention a general lack of understanding of software-intensive systems within industries that traditionally used to be mechanical.

A. *The role of the architect*

The architects’ view of their work is very similar independently of where they work. The architects primarily view themselves as facilitators, involving the right stakeholders in the architectural decisions or problem solving. They also consider themselves as coordinators and communicators of changes influencing the overall architecture. Company I-1 has two different types of architects: system architects and global architects. The global architect is the connection between strategy and business goals. Company I-2 does not have the formal role of an architect, but is currently reviewing their way of working with electronic and electric system development.

B. *Defining architecture*

When asked to explain what architecture means to them, most architects mention structure and form, some mention the building blocks and its interfaces. The user of the system is not often mentioned, only 40 percent. Only two architects mention business aspects and those two are both very senior.

C. *Architectural analysis and synthesis*

The most common methods used are design review meetings and safety analysis. Simulation of network utilization is also performed. One company has a predefined form that they fill in to guide analysis, but it is very rarely used. Alternative solutions are rarely documented. Company A-2 is also the only company in the study having a complete and updated model of the entire system. The defense company D-1 was, not surprisingly, a master of requirement management. Requirement management is performed in the other companies, but not at the same detailed level. The requirement management system is also used to document reasoning of the design decisions.

D. Architectural evaluation and validation

There are no formal evaluation methods used as the ones mentioned in Section 2. Only one company mentioned feedback from test as a way of validating the architecture.

E. Process improvement

The processes at all companies are very similar to the one described in Figure 1, with one big exception: there is no structured synthesis available at any company. Company A-1 is the only company with a defined documented process for architecting. The progress of each task is visualized and controlled during a weekly follow-up meeting.

When asked what they would like to change in their way of working in order to improve, most mentioned how architectural knowledge [10] is managed. The following answers to the question "How do you know if the architecting process is working well?" presents the architects' view of a healthy architecting process:

We do not really know, but the number of changes that are flowing the right way through the change review meeting is an indication.

When new functionality can be absorbed by the architecture without the need of large changes.

When the architecture is clearly communicated and there is no discussion about small issues.

F. Organization

As seen in Table 1, the architectural teams are located on approximately the same hierarchical level relative to the size of the organization. The number of architects in A-1 and A-3 is significantly lower than A-2. This is mentioned as a problem by the architects at both companies. The two global architects at I-1 is the only case where architects have a clear responsibility for coordinating roadmaps.

A-3 is the only company with a large distributed development organization including sites worldwide. They experience difficulties in getting feedback on architectural changes. In the case of I-1 and I-2 the development made on other sites is very encapsulated and they did not experience any large difficulties. I-2 had representatives from the other development sites on the main site. This made the cultural barrier less of a problem.

The historical evolution of the architecting groups differs largely. Company I-2 does not have an architecting team; company A-3 has a very small group considering its size. Company A-1 and A-2 have had an architecting group for a long time, but while the group has been solid in A-1 it has had many different constellations in A-2.

G. Process maturity

In this section, we present an evaluation of the EAMM through informal appraisals at the automotive companies. The results are summarized in Table 2.

Table 2 Summary of EAMM appraisals.

Level	Percentage of maximum score per level		
	A-1	**A-2**	**A-3**
1	100%	92%	92%
2	65%	**37%**	**15%**
3	66%	33%	16%
4	20%	0%	0%
5	**67%**	13%	17%
Total	**3.17**	1.57	1.39

As mentioned earlier Company A-1 is the only company with a defined process, which explains the higher score on Level 3. Company A-1 also has the highest total level and has a surprisingly high score on level 5 considering its low score on level 4. Companies A-2 and A-3 are struggling to exceed Level 1. However, there is a significant difference between A-2 and A-3 at level 3.

Looking deeper into the EAMM data, we find that the most significant items are related to architectural analysis and synthesis, architectural evaluation and validation, and process improvement, whereas the role of the architect, the definition of architecture, and organization are not emphasized in that study.

Regarding analysis and synthesis, the EAMM data confirms that requirements analysis is a weak area. Most companies collect needs from stakeholders, but these are not translated into formal requirements, and routines for managing changes and ensuring traceability are lacking.

In the evaluation and validation of the architectural solutions, EAMM also point out improvement opportunities. Usually, only a single alternative solution is produced, and it is not subject to an evaluation based on a pre-defined set of criteria. Since the organizations are not working with formally defined requirements, verification is difficult, but they do engage in validation. However, only at Company A-1 are there pre-defined routines for how this should be done, and the other organizations rely on ad hoc procedures.

When it comes to process improvement, the EAMM appraisals identify two fundamental areas of concern: the lack of process description (except in Company A-1) and the fact that no measurements are made of process performance in any of the companies. In the previous section, architects presented some characteristics that a well-functioning process should have, but they are subjective and not quantified, and this makes it impossibly to assess the order of magnitude of the problems, and also to trace back the root cause to specific practices employed by the architects.

In summary, when triangulating our data with that of the previously collected EAMM appraisals, many of the identified issues are reconfirmed, and we therefore believe that the validity of our findings is high.

VII. DISCUSSION

The findings presented in the previous chapter are facts found analyzing the answers of the interviews. During the visits to the companies the authors have also built their own understanding of what the differences in how architecting is done depend upon. Those thought are presented below.

The different types of customer of the final products create different architectural concerns. The magnitude of the investment for the customer of products delivered by companies D-1 and I-1 are mostly small (Table 1). This might be the reason why cost seems to be of lower priority at those companies. In contrast, at A-2 where the magnitude of the investment for the customer of the product is very high (Table 1), cost is mentioned very often.

Kruchten [11] suggests that the productive time spent by architects can be classified into three categories of communication: internal (architecture design), inwards (input from outside world) and outwards (providing information). He argues that they should be roughly in the ratio 50% internal, 25% inwards, and 25% outwards. It is very hard to measure this in practice and we have not done so in this study, but communication patterns can still be observed. Even if no extreme variation can be seen, the understanding from this study is that there is a clear difference between the companies. The architects tend to be more satisfied when the inward and outward communication is distributed evenly and where the internal work is of significant size. Company A-3 and I-2 are examples of where the low number of architects supporting a large organization makes the time available for architecting too short. This results in architecting being performed by the developing groups without taking into account the overall system.

The power centers of an organization also affect how the work with the architecture is done. In the companies with a strong line organization, the line controls the architecting process, while in the companies with a strong project organization the process is controlled by the project. At company A-2 the power of development lies in the projects (Table 1). The pressure from the projects might be the reason why the end customer is sometimes neglected. This could be the reason of the over-the-wall tendency meaning that the deliveries of the documents are more important than the knowledge within. The low scores on EAMM Level 3 of company A-3 is surprising considering its high degree (80%) of in-house development. Having so much development in-house should improve product integration, but instead company A-3 has lower scores than A-2 with only 10% in-house development.

The historical growth by acquisition and the many geographical locations of the R&D organization in company A-3 could be one reason of the low maturity level. The relatively low number of architects is also a possible reason. The low number also indicates that the company does not invest as much in architecting.

VIII. CONCLUSION & FUTURE WORK

This paper has presented the current state of architecting practices in three different industrial segments characterized by being software-intensive. For academia it presents a current view of how architecting is performed. The industrial reader is given a list of practices that can be used as inspiration to improve the current architecting practice.

Many of the differentiating practices found in the study can be explained by the context of the different companies. The use of global architects with their own budget in I-1 is a solution to initiate long term architectural projects without having a customer order. The high degree of documented reasoning in D-1 is caused by the high degree of customer specific demands and large orders of very similar products. This forces the architects to make branches of the architecture to fulfill the customer demands and the reasoning is then used to ensure quality.

The defined architecting process found at A-1 and the use of visualization tools to track progress is explained by influences of Lean. The relatively high maturity of this organization could also be explained by the Lean influences as well as the surprisingly low maturity score on level 4 and high score on level 5. This is because their Lean implementation does not push for statistical evaluation instead deviations are caught through weekly process evaluations. Other practices such as the divided architectural teams in A-2 and the lack of formal architects in I-2 are more difficult to explain. We see a clear correlation between the perceived maturity level [4] of the different organizations and how knowledge is shared.

It would be very interesting to make an appraisal of the other companies in the case study to investigate the connection between process maturity and architecting practice. An educated guess based on the interviews is that D-1 would get a score around 2 and I-1 would be similar to A-3. Company I-2 would probably get the lowest score.

There are large differences between the companies and from the view of this study A-1 seems to be in better shape than the others. It is therefore important to note that all the companies involved in the study are making premium products and performing very well financially. Company I-2 does not have an architecting role or process, but still has more than 50% of the world market in its field. So even if the architecture has a strong connection to business context this case shows how business success can be achieved with poor architecting. A more mature architecting practice would probably help and company I-2 is currently improving its architecting practice.

It would also be interesting to make a longitudinal study in order to see how the practice evolves over the years. During the study it has been seen how the balance of power between line and project strongly affects how work is done. This relation would be of interest in a future study. The connection on how business strategy concerning Cost, Quality and Time-to-Market affects architecting could also be further analyzed.

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