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Model-Based System Engineering Adoption in the Vehicular Systems Domain

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***Abstract*—As systems continue to increase in complexity, some companies have turned to Model-Based Systems Engineering (MBSE) to address different challenges such as requirement complexity, consistency, traceability, and quality assurance during system development. Consequently, to foster the adoption of MBSE, practitioners need to understand what factors are impeding or promoting success in applying such a method in their existing processes and infrastructure. While many of the existing studies on the adoption of MBSE in specific contexts focus on its applicability, it is unclear what attributes foster a successful adoption of MBSE and what targets the companies are setting. Consequently, practitioners need to understand what adoption strategies are applicable. To shed more light on this topic, we conducted semi-structured interviews with 12 professionals working in the vehicular domain with roles in several MBSE adoption projects. The aim is to investigate their experiences, reasons, targets, and promoting and impeding factors. The obtained data was synthesized using thematic analysis. This study suggests that the reasons for MBSE adoption relate to two main themes: better management of complex engineering tasks and communication between different actors. Furthermore, engagement, activeness and access to expert knowledge are indicated as factors promoting MBSE adoption success, while the lack of MBSE knowledge is an impeding factor for successful adoption.**

I. Introduction

MODEL-Based Systems Engineering (MBSE) [1] is an approach devised to take care of issues frequently encountered in traditional document-based system engineering (DBSE). In MBSE practice the systems engineering team performs its engineering life cycle activities in a modelling tool, using a dedicated semi-formal modelling language and applying a modelling method, to construct one primary systems engineering artifact — a system model which is inherently coherent and consistent [2]. The great appeal of MBSE is that it, when practiced correctly, promises a return on investment (ROI) that appears late in the Systems Engineering life cycle due to reduced costs in change management. However sometimes stakeholders also incorrectly assume that MBSE makes every systems engineering activity easier and cheaper [2].

Douglass [3] suggests that adoption of MBSE is a challenging change process featuring four partly overlapping phases - assessment, planning, piloting/early adoption, and deployment, where the level of success in each phase depends strongly on the quality of the work that has been done in the previous phase. The empirical results of a study by Rogers and Mitchell suggest that the investment cost for transitioning to MBSE could be considerable and that the adopting organization might have to display patience regarding the ROI [4].

Due to the challenges and the complexity, studying MBSE adoption cases in an industrial context is of high value for other industrial organizations aiming to adopt MBSE. Especially understanding the intentions and related experiences when organizations are setting out for MBSE adoption will provide valuable knowledge upon which future adoptions can be based.

This paper presents an exploratory interview study searching for MBSE adoption purposes, targets and factors promoting or impeding success. The participants in the study were interviewed about their individual experiences related to the above. Three research questions were defined in this study:

- RQ1. What are the primary reasons for and targets in MBSE adoption?
- RQ2. What factors are promoting success in MBSE adoption?
- RQ3. What factors are impeding success in MBSE adoption?

The study was conducted by interviewing practitioners and other stakeholders and applying thematic analysis to the data collected in the interviews to identify themes for each of the research questions. Reasons for MBSE adoption were grouped into two different themes – manage complex engineering tasks better and achieve effective communication and collaboration. Factors promoting MBSE adoption success were also grouped into two different themes – activeness and engagement and access to MBSE expert knowledge. The factors impeding MBSE adoption success were collected under one theme – insufficient MBSE knowledge.

A. Background and Related Work

Douglass [3] suggests that the adoption of a new approach encompassing a new language, such as MBSE with SysML, is characterized by four overlapping phases - assessment, planning, piloting/early adoption, and deployment. In this section, we survey some work related to these MBSE adoption phases.

1) Reasons and targets: Mitchell et al. [4], [5] have performed empirical case studies on the transitioning to MBSE in a system-of-systems product family organization. The primary purposes of the transition were to keep up with the increasing workload, increase automation in the systems engineering workflow, eliminate duplicate data, enhance manual quality assurance, enhance change impact analysis, achieve the automated generation of an interface description language, improve data integrity, and reduce the cost of quality assurance. Carroll et al. [6] have found that the arguments justify MBSE adoption that will enable improvement of engineering efficiency and prevention of costly rework. In addition, Chaudron et al. [7] have synthesized empirical evidence regarding the effectiveness of UML modeling in software development. The study concludes that the two ultimate benefits of UML modeling are improved quality and higher productivity, both of which stem from the direct benefits which UML modeling brings to the developer and the team – UML modeling stimulates the developer to think harder and hence better understand the problem domain and the solution space.

2) Factors promoting and impeding success: Mitchell presents some lessons learned from MBSE introduction [5] — there is a big learning curve to consider, the strive for efficiency requires re-engineering the business process, and if consistency is important, one has to manage human resistance.

Amorim et al. [8] have performed a study to find strategies and best practices for MBSE adoption in the embedded systems industry. They conclude that the advantages of MBSE shall be made clear to the adopting team, the organization shall start the adoption on a small scale, and all engineers should get at least basic MBSE training. Hallqvist et al. [9] have done an empirical study on the introduction of MBSE by using systems engineering principles. In their study, they presented several lessons learned, namely to keep the focus on the purpose, start small while thinking big, address all stakeholders, involve people that have gone through a similar process before, have leadership present who understands people, have a communication plan, and consider using prototyping for validating changes. Madni and Purohit [10] proposed a framework for analyzing investments and potential gains when implementing MBSE. Their results support the view that MBSE requires an upfront investment, with gains showing up in later system life cycle stages. They mention several gains of MBSE such as early defect detection, reuse, product line definition, risk reduction, improved communication, usage in the supply chain and standards conformance that are important. Suryadevara et al. [11] imply that significant investment, a considerable learning effort and attainment of good tool interoperability are components required for success. Selberg et al. [12] have studied MBSE adoption in a company, based on which they give recommendations for adopting MBSE. Their recommendations are to clearly define the purpose of the adoption, assemble a core team, plan for the changes, allow sufficient time, and provide sufficient training to all stakeholders.

What is scarce in the current work is granularity and visibility of data associated with parties and phases in MBSE adoption, including parties who have little or no direct contact with the model and including the phases from assessment to deployment. More empirical knowledge is needed on these facets of adoption.

II. Method

This study was conducted through semi-structured interviews, following Strandberg [13] as the primary interview guidelines. The interviews were transcribed and then analyzed using Braun and Clarke's guidelines for thematic analysis [14]. For more information on the method used we refer the reader to the extended technical report of Gustavsson et al. [15].

A. Planning

To plan and keep track of the work, an interview survey plan was written according to the guidelines by Linåker et al. [16]. As the work on the interview study progressed, the plan was also used to record changes. First, a raw survey instrument with 22 questions was created. In a workshop amongst the authors, we refined it and organized it into initial question groups (topics). Then, in a series of iterations, we created and refined a survey instrument. Each interview was planned with a start session where we would explain the purpose and motivation as well as the interview process. The first topic in the instrument focused on the interviewee (e.g., background, work experience and knowledge related to MBSE). In contrast, the last topic was related to successes, setbacks, and other experiences during the adoption and deployment of MBSE.

B. Interviews

We recruited a convenience sample of individuals affiliated with an organization in the embedded system domain. Using a stratified design to ensure experience and specialization diversity related to MBSE, we selected individuals from the following groups: managers, modelers, and model users. The interviewees were selected from a diverse set of MBSE adoption projects inside the company using a convenience sample based on our contacts in the company. In total, we recorded about 11 hours of audio material.

C. Transcription and Thematic Analysis

The interviews were transcribed using reflective journalism transcription [17] into 109 pages of text. During the transcription, we ensured the anonymization of the transcript. Text coding, was done in the following way: One interview was independently coded by all three authors and the three results were compared, discussed and adjusted to build consensus on the procedure. The remaining interviews were coded by two authors independently, and then discussed in a joint workshop to align the alternatives and agree upon a final coding. For the thematic analysis, we used the Braun and Clarke method [14] and the Halcomb data management steps [17]. A preliminary thematic analysis was done by the first author to elicit a first version of the main themes and then thoroughly reviewed by the other authors based on both audiotapes and interview notes. Next, we iterated on the sets of themes. This activity ended with a workshop with all authors where the final set of themes was agreed upon.

III. Results

We start this section with an overview of the organization and interviewees (also outlined in Table I). Then, the main part of this section covers the thematic analysis results, the overall thematic map in Figure 1, and the answers to our research questions. For more details on the results we refer the reader to the extended technical report of Gustavsson et al. [15].

TABLE I: Interview participants including roles in adoption, expertise domain, self rated MBSE knowledge before and after adoption, and the adoption cases in which they were involved

Interviewee	Role in MBSE adoption			Expertise domain	MBSE knowledge		Cases				
	Modeller	Model user	Team manager		Before	After	1	2	3	4	5
#1	x	x	x	Mathematical modelling, 5 years	1	3	x				
#2			x	Product functions, 27 years	2	5		x			
#3		x		Software design, 6 years	2	2	x				
#4	x		x	Product functions and project management, 8 years	2–3	3			x		
#5		x		Safety related embedded systems engineering, 8 years	2	2	x				
#6	x	x		Safety software architect, 11 years	1	2–3	x				
#7		x		Software development, 18 years	1	4	x				
#8		x		Software development and project management, 20–25 years	1–2	2–3	x				
#9	x			Control and systems engineering, 13 years	1	4		x			
#10	x	x		Subsystems functional design and control system functions, 7 years	0	3	x				
#11	x		x	Mechanical engineering, 30 years	1	2					x
#12	x		x	System design, 15 years	4	3	x			x	

A. Context, Organization and Interviewees

We conducted semi-structured interviews with twelve individuals from the same organization. The organization develops embedded systems in the domain of safety-critical vehicular systems and has more than 35 000 employees over many sites. The company is undergoing a transition to MBSE and has started different adoption initiatives in different sites.

Table I provides some basic information about the interviewees, including their roles and expertise areas. The interviewees were also asked to self-assess their MBSE knowledge before and after the adoption. In total, the interviews covered the experience of the interviewees from five different MBSE adoption cases: Cases 1–4 (Adoptions in the deployment phase) and Case 5 (Adoption in the early adopter/piloting phase). Six interviewees had been in more than one role related to MBSE adoption, and one interviewee had been involved in two different cases. The participants can be categorized in the following roles[1]: modellers (seven interviewees), model users (seven interviewees), and team managers (five interviewees). The interviewees have between 5 and 30 years of experience, with an average of 14.4 years. Seven had at least ten years of work experience. Typical domains of expertise for our interviewees were system design and software development, mathematical modelling, mechanical engineering, software architecture, project management and embedded system engineering. Related to their MBSE understanding, most participants rated themselves as having relatively low knowledge before adoption. According to this self-evaluation, most participants have seen their MBSE knowledge improve during their work in each case.

B. RQ1: Primary reasons for adoption and targets in adoption

In this part of the study, we identified two themes. Both themes were related to primary reasons for adoption: to manage complex engineering tasks in a better way and to achieve effective communication and collaboration. Unfortunately, the interview data did not yield any themes on quantified targets.

1) Theme: Manage complex engineering tasks better: MBSE was seen as an enabler for managing complex technical engineering tasks more efficiently and effectively than traditional system engineering methods. The notion of complexity in this context seems to be related to the nature of the technical challenge involved, the sheer size of the task or a combination of the two. An example of such an area was the work related to subsystem interfaces where the model and the modelling tool were considered to provide a better environment: *"MBSE makes interface management very accurate."* Another area where MBSE was considered to provide an attractive capability was requirements verification: *"The big selling point was left shifting verification of the requirements using simulation."*. Other areas include system testing, change impact analysis and propagation analysis, product homologation, reuse of design solutions, and software standardization.

2) Theme: Achieve effective communication and collaboration: MBSE was regarded as a means to facilitate and enable effective communication and collaboration in a way that is not possible without MBSE. A vision presented by a participant was that the opportunity to represent design in a uniform way in MBSE should be exploited such that it facilitates the communication across the entire MBSE organization, as well as with external stakeholders: *"I think the major objective of MBSE shall be to provide a uniform way of representing the design that we are doing... If you want all the regions to understand what others are doing, and with suppliers and things like that."*

C. RQ2: Factors promoting success in Adoption

In this part of the study, we identified the following two themes: (i) activeness and engagement as well as (ii) access to expert knowledge.

1) Theme: Activeness and engagement: When there were partakers in the team who were active, engaged and persistent, this was associated with MBSE success. The interviews gave observations of managers and model users displaying such qualities. Most of the observations happened when the adoption or deployment was hard going and certain team colleagues were showing a tendency to falter. It was also observed that certain valuable features and instruments for promoting success materialized due to the activeness of the management team. One interviewee stated that the model users being engaged in the modelling tasks had a positive effect on the quality of the requirements derived from the model: *"We*

[1]We note here that some participants had overlapping roles as modellers, model users and/or team managers.

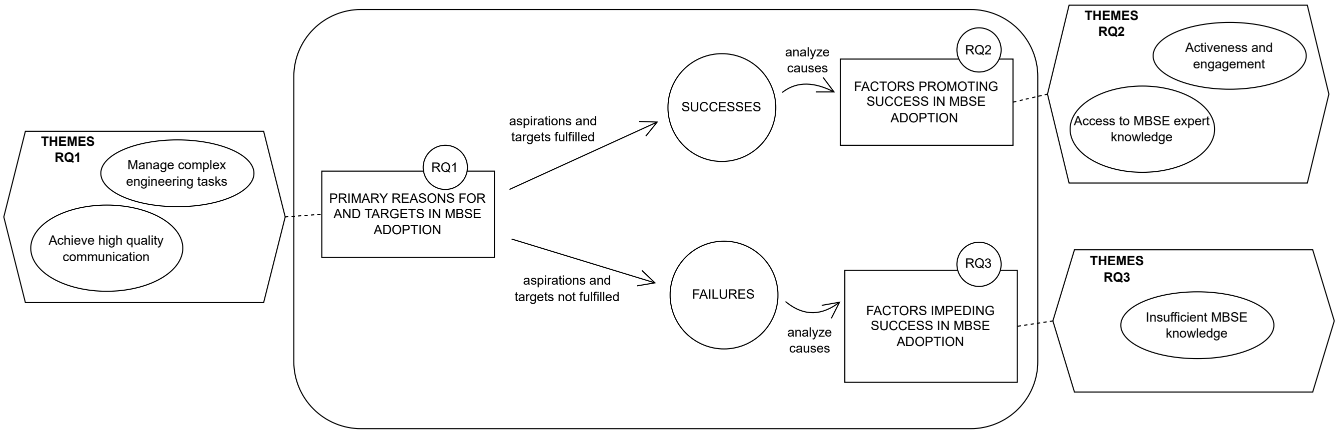

Fig. 1: Overview of the themes and their relation to the research questions.

managed to get the modellers to keep the models updated, then they were thinking a bit extra on their requirements when they were modeling.”.

One participant observed that their company management was active in giving their full support to the MBSE adoption including the deployment. This support helped manage resistance and questioning of MBSE in the organization. The interviewee also linked the management support to the institutionalization of an MBSE core team (i.e., expert knowledge) and the accessibility to the model for the whole team. As the management of resistance, the MBSE core team and the team's model accessibility contributed to the long-term success of the deployment. Related to the successes experienced in the adoption, another participant concluded that these were very much dependent on the adoption team's engagement and their supporting stakeholders in the initial phase of the adoption. These adoption team members had taken the initiative themselves to learn the subject and their stakeholders had also been very active when soliciting input data.

2) Theme: Access to MBSE expert knowledge: A factor behind the MBSE's success was found to be related to present and readily accessible expertise. The instances showing this in the interviews are: (i) the presence of an MBSE core team that assumed a clear long-term role as MBSE process owner, (ii) the provisioning of continuous team support, and (iii) being attentive and adapting to the needs of the MBSE team. Establishing an MBSE expert inside the modelling team in the very early stage of adoption was also perceived as a factor promoting success. For example, one interviewee had an experience where the expert had defined the MBSE process for the team. Another participant had an experience where the expert had acted as a sounding board for the adopters. The expert had even enabled a doubtful adopter to turn into an enthusiast in this role.

D. RQ3: Factors impeding success in Adoption

In this part of the study, we identified one central theme: insufficient MBSE knowledge.

1) Theme: Insufficient MBSE Knowledge: A factor that impedes MBSE adoption success is a lack of knowledge of MBSE. This theme encompasses cognizance on different levels, in diverse areas and among various parties in the MBSE adoption. It appeared in situations when people were, in various ways, dependent on a particular party to make progress in the MBSE adoption. Participants concluded that this involved party had a knowledge gap preventing progress.

An example of such missing knowledge was related to SysML and shown among engineers. While the early phase of SysML adoption among engineers went well, some time into the adoption, an apparent threshold in the overall progress was encountered regarding important concepts in the SysML syntax and semantics. Examples of concepts that caused the adopter's various degrees of difficulty were the two distinct kinds of flows on activity diagrams, ports, and the internals of blocks. For example, one participant mentioned the following: *“When we are getting to more complex things, that is, when we are getting to ports, various types of ports, exactly what they mean and what they do, it is getting more difficult.“* There were observations about a weak cognizance of MBSE among people who were not in direct contact with the model, e.g. people in management. When people in management and other stakeholders were approached by adopters regarding issues that the adopters could not resolve among themselves, flaws in the cognizance of MBSE impeded the possibility to support the adopters or act as sounding boards. As the adopters did usually not have the resources needed to resolve the problems this could cause problems to remain unresolved. Among the engineers, the lack of MBSE cognizance can make them nurture expectations that the deliverables of the modelling team will be definitive and that all subsequent collaboration with that team will be superfluous: *“People expect that we are going to provide them with requirements and everything will be complete and they can leave from there and they will not have to talk to us anymore.”* Insufficient MBSE knowledge could also lead to people comparing model diagrams to other artifacts they could relate to, such as Visio diagrams, whereby they were resisting and questioning the change. It was difficult to bridge this gap by means of argumentation: *"They just think MBSE is just like Microsoft Paint, you know you draw some pictures, it is just like Visio or something"*

IV. Discussion

For research, the findings in this paper are essential as they bring an industrial experience of MBSE adoption and deployment from industrial practice into academia. By understanding that this is not an insignificant process, additional research is possible. Other researchers could add on and revisit MBSE adoption and deployment in other contexts and possibly investigate the results of this study.

Based on our findings, organizations in the vehicular systems domain adopting and deploying MBSE may want to foster activeness, engagement, and access to MBSE expert knowledge in their teams. In addition, companies should pay special attention to the insufficient MBSE knowledge, especially during the adoption phase. There is relatively little data that supports the research question on quantified targets in MBSE adoption. However, in the responses to the interview question, there is considerably more data about primary reasons for adoption. A few interviewees also expressed satisfaction related to the personal gains in learning a new method. However, when asked to suggest the reasons they thought were behind the positive details, the answers did not provide clear reasons. More research is needed to understand these personal reasons and human aspects of learning MBSE.

When discussing the concept of impeding factors, our results suggest that this is a rather multifaceted topic. First of all, the interview questions were framed to stimulate the interviewees to describe a logically coherent story about the MBSE adoption and deployment. One idea behind the design of the interviews was to avoid retrospectively invented opinions from the interviewees about successes and failures but instead, encourage them to base these ideas on observations as to whether the adoption reasons and targets were met or not. Once the successes or failures had been recollected, the interviewees were asked to consider what could have been the cause of each case. As it turned out, the interviewees had many different ways of expressing successes, failures, and factors promoting success or causing failure. One reason for this is that when asked to name challenges and setbacks, participants proposed a predefined view that seemed necessary to be included in the adoption to make it successful.

V. Conclusions

We have conducted an interview study of model-based system engineering adoption and deployment in the vehicular domain. The results presented in this paper are based on semi-structured interviews with twelve practitioners with an average work experience of more than fourteen years and thematic analysis to identify major themes around the reasons, targets, and promoting and impeding factors in model-based system engineering adoption. We discovered that the primary reasons and targets relate to managing complex engineering tasks in better ways and effective communication. Our results suggest that the main factors promoting success are activeness, engagement and access to expert knowledge. A factor that was shown to impede adoption success is the lack of knowledge on different levels and among different parties. Finally, our results show that more research on the model-based system engineering adoption and deployment is needed and that practitioners need to take these aspects more clearly into account.

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