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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 with roles in several MBSE adoption projects 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). Indeed, the use of models at different stages of the engineering lifecycle is an inherent component in general systems and software engineering.

The International Council on Systems Engineering (INCOSE)[1] states some of the system lifecycle purposes that MBSE can serve, namely the possibilities to characterize an existing system, to formulate and evaluate mission and system concept, to specify system architecture design and flow down requirements, to support systems integration and verification, to support training, to capture knowledge and to support design evolution. INCOSE also states some overall benefits which MBSE can bring compared to other systems engineering methodologies. These are improved communications, increased ability to manage system complexity, improved product quality, enhanced knowledge capture, and improved ability to teach and learn systems engineering fundamentals.

Delligatti [2] suggests that MBSE, when practiced correctly, is the solution to the traditional problem of inconsistency between the manually traced artifacts in DBSE. However, while MBSE brings with it significant potential, adoption of MBSE in a traditional DBSE organization is an inherently challenging change to the organization, as it involves fundamental changes in systems engineering processes, methods, tools and languages [3]. It is a strategic development investment where a large part of the investment effort may be placed on human resources. While learning the MBSE technology during the adoption, the engineers will need to be temporarily "pulled out" from the day-to-day work. Hence the adoption must be quite carefully planned, and the technology and the engineers must naturally be fit for purpose when deployed in a commercial enterprise.

Rogers and Mitchell have reported on a longitudinal case study for a product family in a complex system-of-systems environment, where the initial MBSE investment was US$ 3.28M, and it took circa five years from the start of MBSE adoption until the company broke even. However, every year after that, they found a considerable return on the investment. Eight years after the start of adoption, the gross return on investment (ROI) amounted to US$ 10.62M, which meant a net return at that time of US$ 7.34M. Although this is one particular example in a specific environment, it suggests that the investment cost for MBSE could be considerable and that an adopting organization might have to display patience regarding the ROI [4].

There are several important strategic and technical questions to consider when designing and planning such a complex change as comprehensive MBSE adoption. 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 and targets[2] in MBSE

[1]https://www.incose.org/

[2]The terms *reason* and *target* are considered to have separate, albeit related, interpretations in this study. A reason tells us why MBSE is adopted. A target represents incremental or final achievement along the path towards full deployment. Hence a reason for MBSE adoption could be to achieve a particular target.

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. No themes were derived regarding targets during adoption.

The remainder of the paper is organized as follows. Section II presents background and related work, Section III describes the research method, Section IV presents results, Section V contains discussion, and Section VI presents conclusions and future work.

II. Background and Related Work

In this section, we describe the MBSE adoption and deployment background and the related work.

A. MBSE Adoption and Deployment

Laura Hart defines MBSE as follows in an INCOSE chapter meeting [5]:

> *Definition:*
> *"Model-Based Systems Engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phases and continuing throughout development and later life cycle phases."*

Delligatti [2] describes the nature of MBSE. MBSE practice means that the systems engineering team performs their 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. All other systems engineering artifacts, potentially even software source code, are automatically generated as byproducts from the system model. The diagrams constructed in the modelling tool show views of the model, e.g., structure and behavior.

MBSE promises an ROI that appears late in the SE life cycle due to reduced costs in change management. However, sometimes stakeholders incorrectly assume that MBSE makes every systems engineering activity easier and cheaper. Modelling language, modelling method and modelling tools are key concepts in MBSE. The modelling languages are semi-formal languages (often graphical) that are fundamental enablers of system models. The modelling methods complement the language rules by imposing further rules and restrictions on the practitioners. The modelling tools are dedicated tools in which the models are constructed and accessed and from which the systems engineering artifacts are generated. A variety of modelling languages, methods and tools exist, yet tailoring/configuration is often needed when adopting and deploying MBSE.

According to the Cambridge Dictionary[3], adoption and deployment can be defined as follows:

> *Definition:* ***adoption***
> *"accepting or starting to use something new."*

> *Definition:* ***deployment***
> *"the use of something or someone in an effective way."*
> *"the use of something or someone, especially in order to achieve a particular effect."*

Douglass [3] suggests that the adoption of a new approach encompassing a new language, such as MBSE with SysML, is characterized by the following four overlapping phases:

- Assessment
- Planning
- Piloting/Early Adoption
- Deployment

The assessment aims to thoroughly understand and describe the gap between the organization's existing and desired state. The planning of the piloting and deployment phases is largely based on the gap found in the assessment. The piloting/early adoption is a rather extensive period characterized by pioneering, learning, development, and change management. The aim is to achieve ever-improving effectiveness through pilot projects. The deployment is the phase when the prepared resources are launched in the enterprise after proving fit for purpose.

B. Related Work

1) Reasons and targets: Mitchell et al. [4], [6] have performed empirical case studies on the transitioning to MBSE and Model-Driven Architecture (MDA) 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. Some five years after the transition, they concluded that the most significant benefits of MBSE were that it made the organization more efficient, yielded fewer interface defects (i.e., higher product quality), and enabled the uncovering of interface defects earlier in

[3] https://dictionary.cambridge.org/

the test process. The introduction of a SysML model made it possible to visualize the most complex and critical tribal knowledge, which previously was difficult and perhaps even impossible to visualize. The difference in quantity and timeliness of the discoveries of interface defects made the single most outstanding contribution by MBSE to the ROI. MBSE also yielded several additional qualitative benefits which could not be measured but had the potential of providing additional ROI on a larger system of systems.

Carroll et al. [7] have found that the arguments justify MBSE adoption that will enable improvement of engineering efficiency and prevention of costly rework.

Chaudron et al. [8] 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. In addition, the shared UML system model enables the team to communicate more effectively.

Suryadevara et al. [9] have produced an experience report on MBSE adoption in the construction equipment industry. Readily available benefits of MBSE in the short term are improved communication between cross-functional teams, improved traceability between requirements and system artefacts, and the establishment of a single source of information.

To the best of our knowledge, no studies are dealing with the topic of primary reasons and targets related to the adoption of MBSE in the vehicular domain.

2) Factors promoting and impeding success: Mitchell presents some lessons learned from MBSE introduction [6] — 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 ("Smart people like to do things their own way.").

As mentioned in Section I, Rogers and Mitchell report in their case study that MBSE has delivered a significant financial ROI (US$ 10.62M return after eight years on a US$ 3.28M investment) for a product family in a complex system of systems environment [4]. However, in their remarks about the study's limitations, they state that a different modeling tool, model architecture or systems engineering process than they have selected might alter the ROI in any direction and even turn it into a financial loss. This could imply that they think their selections regarding modeling tool (MagicDraw™) and model architecture (closely aligned with their systems engineering process) are success factors that gave them the benefits they desired for a high ROI.

Amorim et al. [10] 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. Furthermore, the adoption pilot project shall receive the financial budget and time it needs and create value for the whole organization.

Hallqvist et al. [11] 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. They also found that a significant change such as the introduction of MBSE includes many stakeholders and requires a holistic view and incremental planning.

Madni and Purohit [12] 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. [9] imply that significant investment, a considerable learning effort and attainment of good tool interoperability are components required for success. They also state that adapted project planning and sufficient resource allocation are needed to obtain the short-term benefits of communication, traceability, and information management.

Selberg et al. [13] 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.

III. Method

This study was conducted through semi-structured interviews, following Strandberg [14] as the primary interview guidelines. The interviews were transcribed and then analyzed using Braun and Clarke's guidelines for thematic analysis [15]. This section describes the details of our method, with Figure 1 providing an overview of the steps.

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

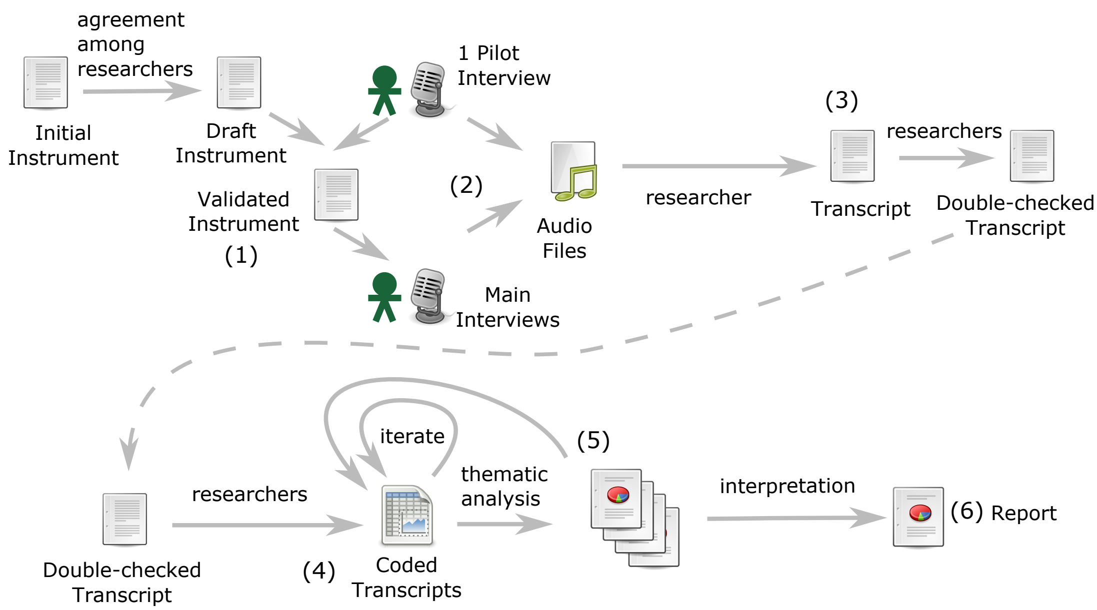

Fig. 1: Overview of the method followed in this interview study: (1) preparing and validating the instrument, (2) conducting and (3) transcribing interviews, and (4) qualitative analysis with thematic analysis that includes manual processing of raw data and resulting themes which were (5) interpreted when reporting the results.

created and refined a survey instrument, step (1) in Figure 1. 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. Regarding the account of experiences from interviewees, we ensured that the data included information on the adoption phase related to each account. We held one pilot interview to validate the instrument, but since no significant changes were made to the instrument after the pilot interview, it was included in the final pool of interviews to be analysed. The validated instrument, (1) in Figure 1, covered five topics, four main topical questions and 22 sub-questions. The questions were open-ended, and most of them had sub-questions to serve as guidelines for the researcher conducting the interview.

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. Interviews were conducted face-to-face when possible. In six cases, this was not possible, and these interviews were done via telephone. The interviews were recorded with a digital voice recorder. The interviewees were given much freedom to express their thoughts, also when discussing topics not covered by the instrument. One researcher conducted most of the interviews, but for the first four, we used two researchers where one was the "driver," and the other researcher contributed with clarifying questions, kept track of time, and made sure no question was forgotten. In total, we recorded about 11 hours of audio material (step (2) in Figure 1).

C. Transcription

The interviews were transcribed using reflective journalism transcription [17] into 109 pages of text (step (3) in Figure 1). For the five interviews that were conducted in Swedish, the transcription process also also involved translation to English. Transcription was performed by hand by the first author. As soon as possible after each interview, to ensure that reflections and notes remained fresh, we reviewed our notes. After the researchers completed their field notes and performed reflective journalizing, the audiotape was reviewed in consultation with the researchers' notes in order to ensure the accurate transcription of the interaction. This required that the transcript be reviewed by other researchers not present in the interview. During the transcription, we ensured the anonymization of the transcript. Personal details, names of individuals and products, or any other information divulging sensitive information, were replaced by codes, such as P1, P2, etc., for projects, T1, T2, etc., for tools, or A1, A2, etc., for geographical locations. All transcripts were read at least once to double-check their accuracy. Sometimes this involved improvements in transcription and anonymization.

D. *Thematic Data Analysis*

There are many approaches to qualitative data analysis; we decided to follow a thematic analysis as described for the field of psychology by Braun and Clarke [15]. We saw this approach as suitable for the type of data we had, and it allowed for one idea in the transcript to be coded as belonging to several themes. Important concepts used in this study are codes, themes and thematic map. Codes are used to capture the essence of why the researcher thinks a particular part of data is valid. A theme is a high-level abstraction as well as a "patterned response or meaning within" the data [15]. A thematic map is a qualitative abstraction of the data, showing high-level connections between themes.

Following Braun and Clarke [15], we began by getting an explicit depiction of parts of the interview data while at the same time conducting a broad coding of the data. For the actual thematic analysis, we did a data-driven analysis, aiming at processing the data without attempting to make it fit into existing research on the adoption and deployment of MBSE. In the initial phases of the thematic analysis, we looked for anything beyond what participants said since we wanted to comprehend the context better while at the same time exploring what interviewees said with no underlying connotation associated with it.

Text coding, step (4) in Figure 1, 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 (step (5) in Figure 1), we used the Braun and Clarke method 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 were agreed upon.

IV. 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 2, and the answers to our research questions.

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 in and outside of Sweden, Europe, and Asia. The development follows the V-model, and at least parts of their products are subject to safety standards. 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). Case 1 is concerned with the deployment of MBSE in the development of a product family. Case 2 is about the deployment of MBSE in the development of new features in an existing product. Case 3 concerned the deployment of MBSE in the development of a product family, while Case 4 was about MBSE having been fully deployed in a system engineering organization. Finally, case 5 involved an early adoption/piloting of MBSE, focusing on variability modeling of a product family.

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[4]: 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. Related to their involvement in specific MBSE adoption cases, eight interviewees were involved in case 1 while two other interviewees were involved in case 2. In addition, one interviewee each from case 3, 4 and 5 were involved.

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: (i) how to manage complex engineering tasks in a better way and (ii) how 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

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

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	

the technical challenge involved, from 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."*

> *Answer RQ1: Our results suggest the primary reasons and targets when adopting MBSE are to manage complex engineering tasks better and achieve effective communication and collaboration.*

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

Another interviewee acknowledged how significant a change it is for an organization to adopt and deploy MBSE. This interviewee observed that individuals showing perseverance were necessary for achieving success: *"If you have some really strong people who are unwilling to compromise, that is a recipe for success in daredevil projects such as this one."*.

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. The interviewee concluded that the support from the company management was a critical success factor.

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 solicited 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

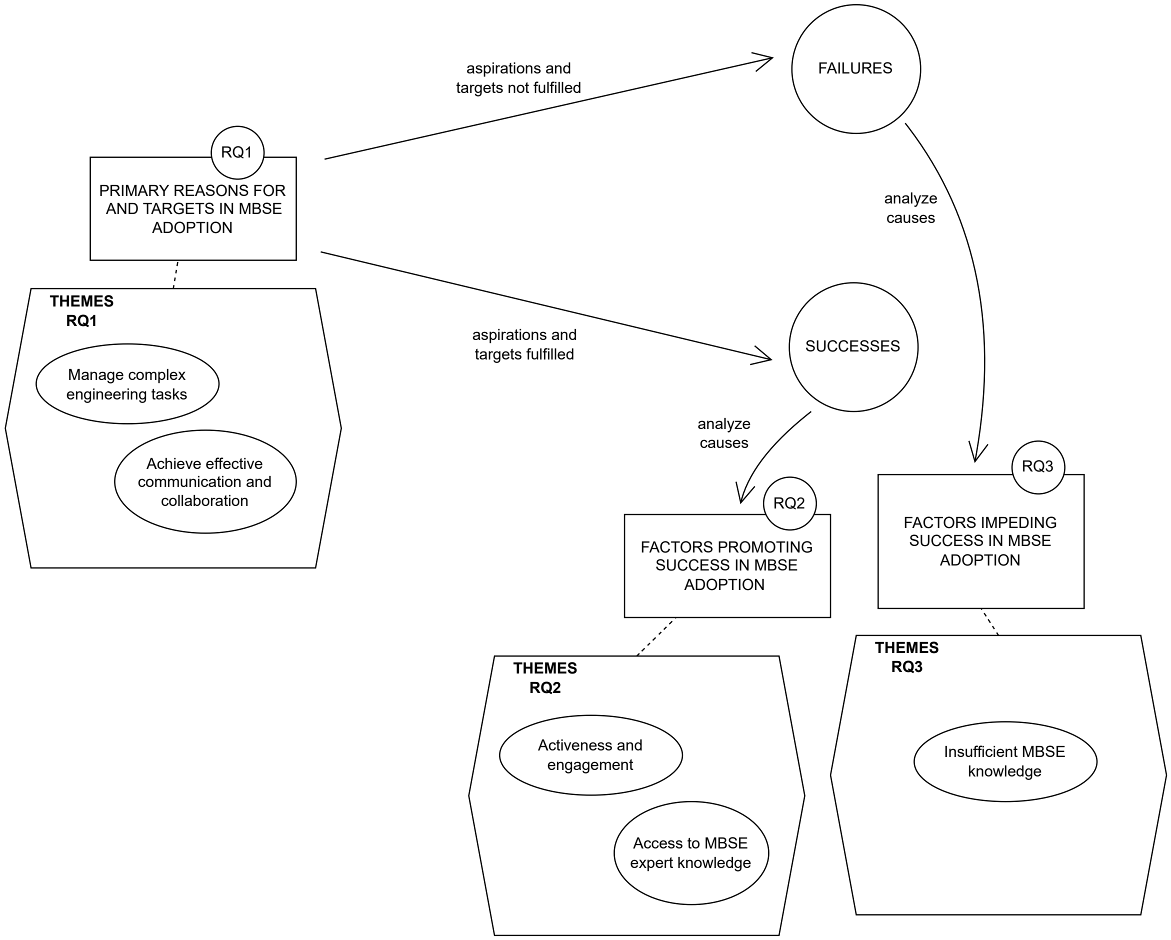

Fig. 2: Overview of the themes and their relation to MBSE adoption.

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.

> *Answer RQ2: The factors promoting success when adopting MBSE were activeness & engagement, and access to MBSE expert knowledge.*

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. These flaws in the progression of the skills development among the engineers were unexpected, and it proved unexpectedly challenging to help engineers bridge such gaps in their knowledge. For example, one participant mentioned the following:

- *"Activity diagrams for example, with the icon flow versus the control flow concept, not everyone knows what it is used for."*
- *"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."*
- *"Structure diagrams that show what the block is composed of and things like that, people have difficulties with that."*

Another example of missing knowledge was when model users realized that they had a many-faceted tool in their hands that could potentially be utilized in many respects when they were reading, reviewing and using the models; however, their tool knowledge was limited, which meant they were only able to exploit a few simple features:

- *"The tool is such a vast tool so you can retrieve a lot of information in very good ways."*
- *"There is probably a lot we could get out from it that we don't even know of."*
- *"It can be difficult when you get a new tool to even know what to ask about."*

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"*
- *"So they don't like this because if it is just pictures, what is the point?"*

> *Answer RQ3: Our results suggest the factors impeding success in adoption are related to the insufficient MBSE knowledge.*

V. 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 factors that promote success. However, in the responses to the interview question about positive experiences and successes, there is considerably more data about the positive aspects of the MBSE process and the model. One explanation for this could be related to a situation in which the interviewees were new to MBSE and its 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.

Many interviewees have brought up many serious flaws they experienced in their organization's MBSE adoption approach. The interviewees were engineers and team managers, which limits the perceived perspectives. Nevertheless, some objective observations were obtained based on the collected data. Most of the flaws the interviewees experienced are connected to an effort that can be directly transformed into a financial investment; even planning an adoption is an effort that must be made even before the adoption begins. Furthermore, an adoption plan is a part of a business case that is needed to evaluate if the adoption should even be done at all. Hence the business case is an investment that can lead to a "No Go" decision, in which the investment does not yield any observable improvement.

A. Threats to Validity

The design of our interview instrument was based on research questions and was reviewed before its use. In addition, we anonymized the interview transcripts. We used a non-random selection of the interviewees. However, since our focus is on real-world MBSE adoption and deployment, we had to select relevant participants inside one company, and therefore random selection was not an option. We were also careful in selecting a variety of roles to interview to reduce the threat of selection bias.

We interviewed participants with more than one type of role. Our focus is on maximizing diversity in roles of participants. Coding of interviews was done by more than one researcher to increase the external validity of the study. We reported the details of our process to support the replicability of our study in similar contexts. Rather than conclusive evidence, our results should be seen in the context of an exploratory study of MBSE adoption and deployment in the industry.

VI. 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 expert knowledge. A factor that was shown to impede adoption success was 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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