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Strategies and Best Practices for Model-based Systems Engineering Adoption in Embedded Systems Industry

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Strategies and Best Practices for Model-based Systems Engineering Adoption in Embedded Systems Industry

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Abstract—[Context] Model-based Systems Engineering (MBSE) advocates the integrated use of models throughout all development phases of a system development life-cycle. It is also often suggested as a solution to cope with the challenges of engineering complex systems. However, MBSE adoption is no trivial task and companies, especially large ones, struggle to achieve it in a timely and effective way. [Goal] We aim to discover what are the best practices and strategies to implement MBSE in companies that develop embedded software systems. [Method] Using an inductive-deductive research approach, we conducted 14 semi-structured interviews with experts from 10 companies. Further, we analyzed the data and drew some conclusions which were validated by an on-line questionnaire in a triangulation fashion. [Results] Our findings are summarized in an empirically validated list of 18 best practices for MBSE adoption and through a prioritized list of the 5 most important best practices. [Conclusions] Raising engineers' awareness regarding MBSE advantages and acquiring experience through small projects are considered the most important practices to increase the success of MBSE adoption.

Keywords—Model-based Systems Engineering, Process adoption, Best Practices, Embedded systems, Empirical research

I. INTRODUCTION

Model-based Systems Engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities. It begins in the conceptual design phase and continues throughout development and later life cycle phases [1]. MBSE is part of a long-term trend towards model-centric approaches adopted by other engineering disciplines including mechanical, electrical, and software.

In this approach, models (as opposed to document-centric approaches) serve as blueprints for developers to write code, provide formalization, tackle complexity, and enhance the understanding of the system. Specialized tools automate much of the non-creative work (which translates to gains in productivity and quality) and generate code based on the models. MBSE foster artifact reuse, improves product quality, and shortens time to market [2].

Despite the aforementioned benefits, adopting MBSE is a complex task, especially for larger and established companies [3]. Process changes are required in all system life-cycle phases as well as a shift in the development paradigm (i.e., abstract thinking [4]) and application of new tools. Projects

are not likely to meet their cost and delivery target when adoption is carried out poorly.

Our goal was to find out what was tried, what worked, what did not work, how the problems were solved, what can be recommended, and what should be avoided when adopting MBSE in organizations that develop embedded systems. For this purpose, we conducted 14 semi-structured interviews with experts from embedded systems organizations. From these interviews, we extracted 18 best practices fitted for tackling MBSE adoption challenges. Sequentially, we validated and prioritized the best practices with the help of an on-line questionnaire which was answered by MBSE practitioners.

Our findings provide input for planning MBSE adoption based on the knowledge of practitioners that went through the experience of implementing MBSE in already established embedded systems development organizations. Our paper makes the following contributions:

- A granular set of MBSE adoption best practices derived from real field experience and validated by practitioners through a questionnaire.
- A prioritized list of the five most important best practices.
- The findings shed light on MBSE adoption issues and how they were overcome by practitioners.

We expect that this knowledge can help organizations to adopt MBSE in a cost-effective and timely manner.

II. STUDY APPROACH

A. Research Objective

The research objective is summarized in terms of the Goal-Question-Metric [5] (a.k.a. GQM) template in Table I.

B. Research Design

For this study, we devised an inductive-deductive research approach in a triangulation fashion [6] composed of three main activities as depicted in Fig. 1. Inductive reasoning is used to build hypotheses and theories. However, inductive reasoning allows for the conclusion to be false [7], thus we applied deductive reasoning to our findings. Such measure also addresses some threats to validity (cf. Section II-C). The activities are described in detail in the following paragraphs.

TABLE I
RESEARCH OBJECTIVE

| | |
|-----------------------|---|
| Analyze | MBSE adoption |
| for the purpose of | increasing efficiency (i.e., cost and time) |
| with respect to | adoption strategies and best practices |
| from the viewpoint of | engineers that participated or observed some endeavor to introduce Modelbased Engineering in a organization |
| in the context of | embedded systems industry. |

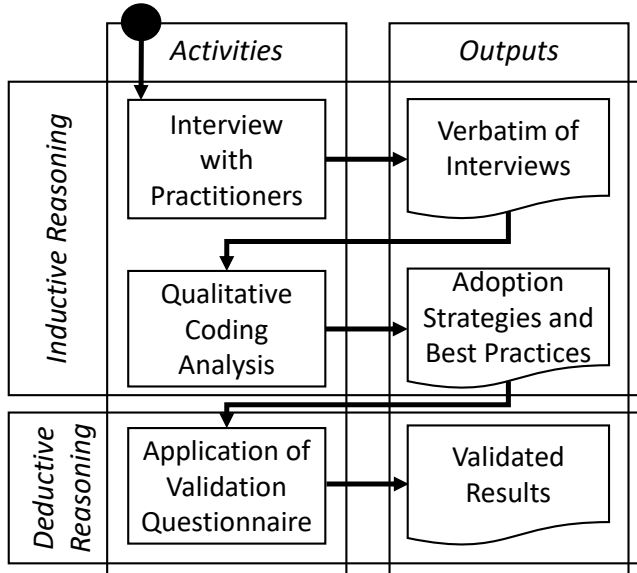


Fig. 1. Research work-flow

1) *Inductive Reasoning*: At the inductive phase, we followed an exploratory research approach [8] with the goal to identify MBSE adoption strategies and best practices from the experience of experts. The method provides insights into the examined topic and gives essential information to understand the phenomenon in its real context [9], [10]. Semi-structured interviews were used to collect the data, qualitative coding analysis [11] was used to analyze the data.

Interview with Practitioners. We conducted 14 face-to-face interviews, each taking around 60 minutes. We developed an interview guide [12] that was structured along a funnel model [10]. It started with general questions about the participant's context and the understanding of MBSE. Afterwards going into detail about specific topics such as employee training, process and tooling selection, and adoption experiences. The interviewee selection was based on two criteria: First, the interviewee should have work experience of several years. Second, the interviewee should work in an environment where MBSE adoption is a realistic option. Therefore, we restricted the group of interviewees to people working on embedded systems or within this context. The participants were screened from work contacts of the authors and industrial partners that participated in a research project¹ with focus on MBSE adoption in practice. Table II provides an overview of the participants and respective demographic

¹<https://spedit.in.tum.de/>

TABLE II
INTERVIEW PARTICIPANTS

| ID | Industry Sector | Type of Company | Role of Participant |
|-----|-----------------|-----------------|----------------------------|
| P1 | Tool vendor | OEM | Technical Sales |
| P2 | Tool vendor | Academic | Professor |
| P3 | R&D services | SME | Manager |
| P4 | Automotive | OEM | Head of Development |
| P5 | Automotive | OEM | Systems Engineer |
| P6 | Medical | SME | Head of SW Development |
| P7 | Automotive | Supplier | Function Architect |
| P8 | Automotive | OEM | SW Architect |
| P9 | Research | Academic | Professor |
| P10 | Automotive | Supplier | Developer |
| P11 | Avionics | OEM | Team Lead |
| P12 | Electronics | OEM | Head of SW Development |
| P13 | Avionics | SME | Head of System Engineering |
| P14 | Robotics | OEM | Team Lead |

data. In consent with the interviewee, the interviewer took notes for detailed analysis. The outcome of this activity is the Verbatim of Interviews, which is input for the next activity.

Qualitative Coding Analysis. Three researchers analyzed the interviews using qualitative coding [11] and managed using the qualitative data analysis tool ATLAS.ti². Neither of them participated in the interview phase. The analysis started with all three researchers working on the same five interviews. The results were later discussed and merged in a meeting. We used the discussions to homogenize the understanding of the codes among the researchers [13] (i.e., what/how to look for). The remaining interviews were tackled in a cross-analysis fashion. In a round with all three researchers, the unresolved conflicts were ironed out. The outcome of this activity was a list of Adoption Strategies and Best Practices for MBSE adoption.

2) *Deductive Reasoning*: Rather than obtaining new information, our goal in this phase was to validate our previous finding through triangulation [6]. For this mean, a questionnaire was built based on the findings of the previous activity and distributed among practitioners.

Application of Validation Questionnaire. The questionnaire respondents were screened from two research projects mailing list, CrEst³ and SPEDiT⁴, and two MBSE discussion groups from a business and employment-oriented social network⁵. Our anonymous questionnaire had three parts. In the first part, we asked for demographic data (organization size (cf. Fig. 2), industry sector (cf. Fig. 3)) and added a yes/no question whether the respondent has ever participated or observed some endeavor to introduce Model-based Engineering in an organization. We used this question to exclude respondents without proper experience. We had 40 respondents in total, 3 were excluded. In the second part, we asked the respondents to express their agreement with each best practice (BP) using a Likert scale [14] with four levels: Strongly Disagree, Disagree, Agree, Strongly Agree. In the last part, we asked the respondents to select up to 5 BPs that they considered most important.

²<http://atlasti.com>

³<https://crest.in.tum.de/>

⁴<https://spedit.in.tum.de/>

⁵<https://www.linkedin.com>

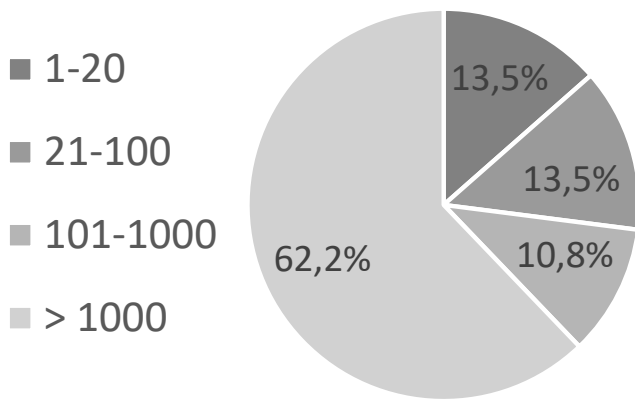


Fig. 2. Organization size of the questionnaire respondents (i.e., number of employees)

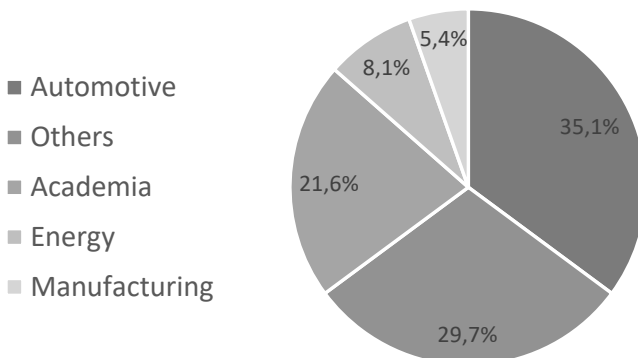


Fig. 3. Industry sector of the questionnaire respondents

Section III contains the output of all activities and respective discussion.

C. Threats to Validity

The validity of our results is subject to the following threats:

Sampling bias. All interview subjects work in Germany (omission bias). They were selected from a convenience sample of project partners and professional contacts (inclusion bias). To mitigate these issues, we created the questionnaire and distributed it to a broader audience (i.e., triangulation).

Researcher bias. To mitigate this threat, the interviews were conducted by two researchers who took notes independently. Further, the interpretation presented in this paper was validated through a questionnaire.

Research method. To minimize misunderstandings between interviewees and the researchers, the study goal was explained to the participants prior to the interview. Steps taken to improve the reliability of the interview guide included a review and a pilot test. We followed several strategies as proposed by Maxwell [15] to mitigate threats.

External validity. We expect that our results are representative for the embedded systems industry, thus we cannot generalize the results to other types of industry.

D. Availability of Data.

Due to unreasonable effort necessary for anonymizing the interview transcripts, we do not disclose them. However, we

disclose the interview guideline, the questionnaire, and the results of the questionnaire⁶.

III. RESULTS AND DISCUSSION

In this section, we present and discuss our findings, which are shaped in the form of Best Practices and are classified in four groups:

- Piloting - what to care about at the first attempts
- Tool and process - selection and adoption decisions
- Knowledge building - development of team competence
- Management - human resources motivation and support

This section is divided as following. Next subsection presents all best practices, the following four subsections describe the groups and associated best practices. We present quotes as evidence and the result of the questionnaire. We also discuss related existing work. In the last subsection, we present the list of Best Practices that are the top five most selected best practices.

A. Summary of Best Practices

The identified best practices and their respective groups are summarized below:

Piloting

- BP01: The organization should start adopting MBSE with new projects.
- BP02: The pilot project should create real value for the organization (i.e., no didactic project).
- BP03: The pilot project should have enough budget and time allocated to bear the overhead of adoption.
- BP04: No translation of old artifacts, exception is when considering reusable artifacts.
- BP05: Start small in terms of project and team size in order to acquire some experience.

Tools and Process

- BP06: Tools with open interfaces and homogeneous work-flow are preferred.
- BP07: All engineers should have access to the tools.
- BP08: Tool acquisition is very costly therefore should be thoroughly planned.
- BP09: Have the new MBSE processes well documented so you better understand what tool you will need.

Knowledge building

- BP10: All engineers should get, at least, basic training in MBSE.
- BP11: Using examples that are familiar to the domain of the organization eases the understanding. Model some existing artifacts for using as examples.
- BP12: Many strategies can be used to build knowledge of an organization, the context should be taken into consideration.
- BP13: There should be a planned form of later evaluation to fill eventual gaps.

Management

- BP14: Make the advantages of MBSE clear.
- BP15: Have technically prepared people to support your engineers (i.e., not sales personnel).
- BP16: Bring everyone to adoption (i.e., avoid creating castes).

⁶<https://figshare.com/s/e5e2c5535282ae60fb29>

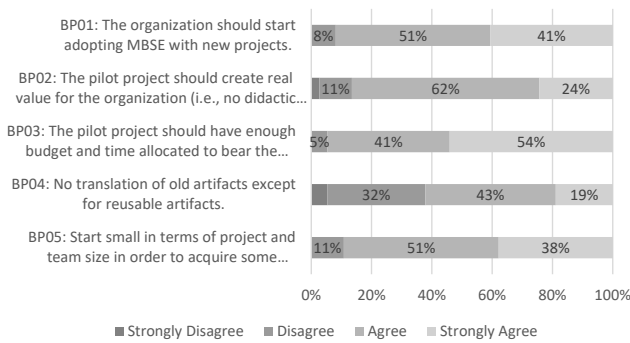


Fig. 4. Questionnaire results for Piloting group.⁷

BP17: If you have good engineers let them do the work for you, it is cheaper and they will engage more (i.e., empowering).

BP18: Management should unify all employees towards adoption.

B. Piloting

This subsection describes best practices related to the initial attempt to implement MBSE and how to harvest benefits from it. The results of the questionnaire for the best practices of this group are depicted in Fig. 4. In general, the respondents agreed with most of the BPs. BP03 got the most agreement (95%) among its peers. On the other hand, 38% of the participants disagreed with BP04. Our hypothesis is that respondents that have no reuse culture in their organizations are likely to disagree with this BP.

BP01: The organization should start adopting MBSE with new projects.

“New projects with MBSE” (P14)

“Do not recycle the past” (P9)

“No migration of old projects” (P8)

“New start in new project preferred” (P1)

“Set up own project for method development instead of accompanying from series development” (P3)

“Remove [team] from existing organization, set up your own project, the rest continues as before. Within a few years, new product generation has higher market share.” (P10)

Introducing MBSE through new projects was a good practice pointed out by many interviewees. By doing so, effort would not be wasted with re-work of existing artifacts that might just be archived in a near future. Starting from scratch also prevent developers to shortcut the work-flow with information that is already documented thus compromising the learning of the method (i.e., there is no document version for referencing the possible incomplete information). Additionally, already running projects have fixed budget and deadlines that do not consider such overhead. Meeting those constraints gets harder when the engineers need to concentrate on learning MBSE.

“Legacy stay where they are” (P14)

⁷BP02 and BP04 received 3% and 6% respectively of ‘Strongly Disagree’.

“Existing projects remained in old surroundings and were gradually archived” (P1)

“Backwards compatibility, so that only changes need to be redesigned (includes not only code, but also specs, tests, test infrastructure)” (P10)

As MBSE became more pervasive in the organizations, the old document-based projects were naturally phased-out. Exceptions for this are Product Line intensive organizations or organizations with high reuse levels. In this case, translating the existing document-based artifacts that are meant to be reused to model-based artifacts is a recommended practice.

BP02: The pilot project should create real value for the organization (i.e., no didactic project).

“Start with a concrete project” (P9)

Learning MBSE through a real project with real deadlines and milestones is reportedly better than learning through mock up projects and generic examples. The real-life setting boosts engineers’ motivation since their work is already producing something useful. Additionally, real projects are related to the domain of the organization.

BP03: The pilot project should have enough budget and time allocated to bear the overhead of adoption.

“The first projects must be able to bear the burden.” (P9)

“Business case because of investment hurdle in the beginning” (P12)

The effort needed by engineers to learn should be considered when deciding for the pilot project, which must be able to bear the burden i.e., managers should avoid using critical (time-wise, business-wise, technology-wise) projects for this matter. By doing so, managers can mitigate the risk of a project failing to meet its constraints or MBSE being not properly implemented.

BP04: No translation of old artifacts except for reusable ones.

“Parts with re-use are taken over” (P14)

“It started with reverse engineering. The existing system was clustered according to the information model” (P7)

Despite the support for using new projects, converting the existing document-based artifacts that are prone to re-use was also a strategy presented by some respondents. Such artifacts are well detailed thus allowing the developer to concentrate in the methodology rather than the content. Moreover, the newly created models can be compared to the existing document-based version for verification and validation of the models. It is important to chose artifacts that are going to be reused in future MBSE projects otherwise the effort will just be used for learning purposes.

BP05: Start small in terms of project and team size in order to acquire some experience.

“Only 1-2 people, then the rest of the team” (P14)

“Start in some areas that you can better oversee [...] Best to start in individual areas according to company guidelines” (P6)

“Often pilot installation to gain experience, then expansion companies-wide” (P1)

“It is advisable to start with a partial introduction first, later through a consistent MBE. - needed breath” (P2)

“Introduction as ”submarine project” by dedicated developer, then application in own department, now overarching roll-out.” (P5)

“If necessary implementation strategy with 3-4 months observation of what the developer does, and then decide how to improve the process with MBE” (P2)

Starting with a small, highly motivated group of employees in a grassroots strategy fashion is likely to increase the chances of success. Such practice allows the training the implementation in an easily controlled setting and identification of characteristics that are exclusive to the organization (current processes and auxiliary tools) and its domain (development of DSL). Thus, issues can be identified with more precision and addressed promptly. Once the small group develops acquaintance with the new tasks and tools, the implementation should be rolled out to the rest of the team.

Related work. Investments in training, tools and modeling environment should be considered in the projects selected for initially applying MBSE. Expectations should be handled so proper time is given for the effort to pay dividends [16]. The experience of Fosse and Bayer [16] made the authors support the “learning by doing” strategy in real life projects by keeping the focus on project deliverables and modeling as needed. According to the authors, the pressure to deliver real engineering products forces discovery and resolution of problems not likely encountered in a didactic-only project. The authors stated that it is possible to yield communication and understanding improvement at an earlier stage by focusing at description first, then analysis. Hutchinson et al. [4] state that “starting small” when adopting MDE and then growing, thus committing more resources on a wider scale is a helpful response towards MDE adoption.

C. Tools and process

Tools are an important cornerstone of MBSE. Traceability, simulation, automatization of task are among the things that are only possible with the use of specialized tools. However, tool licenses are expensive and new tools require learning investment. Rolling back tool acquisition is very costly, thus wise decisions can save time and resources. Proper tool selection requires identifying what capabilities the organization would like to develop by implementing MBSE and acquire the tools that will help it fulfill its goal.

Figure 5 shows the survey results for Tools and process best practices. We can see a fairly amount of agreement among the respondents and very few disagreement responses.

BP06: Tools with open interfaces and homogeneous work-flow are preferred.

“Customers want homogeneous tool chain but open interfaces” (P1)

“Often the entire tool chain is replaced” (P1)

Because MBSE is so complex and encompasses the complete system development life-cycle, supporting tool chains are often equally complex. Currently, several tools

are required to do the job because existing ones are not developed enough to cover the whole life-cycle. For this matter, import and export features must allow the work to continue in further design phases without much ado, thus interoperability through open interfaces becomes a very desirable characteristic. By seeking open interfaces tools, the organization protects himself of many problems that using exclusive proprietary tools can bring.

BP07: All engineers should have access to the tools.

“The worker level must also get the tools” (P9)

“Tool usage for all developers who use the tools” (P6)

MBSE tools should be widely available for all engineers. Failing to do so can create two classes of engineers and this could jeopardize the adoption. However, some engineers are mainly producing models while others are mostly consuming them for some activity. Therefore, understanding how the tools and models are going to be used can lower acquisition costs.

BP08: Tool acquisition is very costly therefore should be thoroughly planned.

“Develop an adoption strategy” (P8)

“Development of a holistic approach/methodology” (P1)

Defining well and in advance the new process is highly recommended. Planning should be done considering full implementation of the processes and tools. This measure avoids realizing at a later point in time that the decisions taken when planning the MBSE adoption (tools to be acquired, processes to adopt, training contents) are not fitted for further intended process maturity. The consequences of this mis-happen can be manifold: from extra effort to work out tool inter-interoperability, until costs with redundant tool acquirement and waste of time with training.

BP09: Have the new MBSE processes well documented so you better understand what tool you will need.

“If the standard process is well documented, the MBE implementation will work easier.” (P1)

Organizations that have their current development process described and documented as it is performed have less trouble when implementing MBSE. The tasks and artifacts to be replaced can be straightforwardly identified and consequences of the change are easily identified.

“First the process was set, then the tool decision” (P7)

In MBSE, tool and process are highly intertwined. It is not uncommon that tool manufacturers provide also the process work-flow specially designed to be used with their tool. Thus, tool selection is also a contributing factor when choosing which MBSE process to adopt.

“Tool support for automation of work” (P12)

Automation of work is one of the best features provided by MBSE. The formality of models allow tools to automatically verify many properties that otherwise would require intensive human labor. While some capabilities are indispensable, others might be just nice to have. By understanding which features bring the best benefits to the organization (now and in the future) a better cost benefit

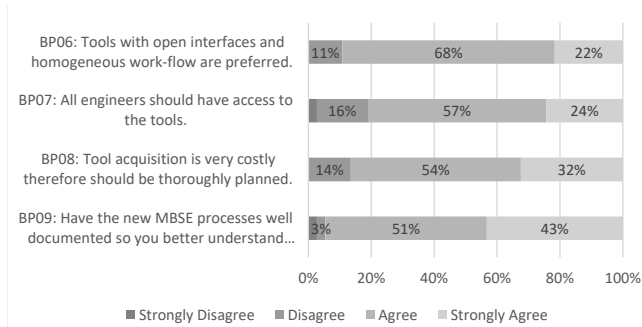


Fig. 5. Questionnaire results for Tools and process group.⁸

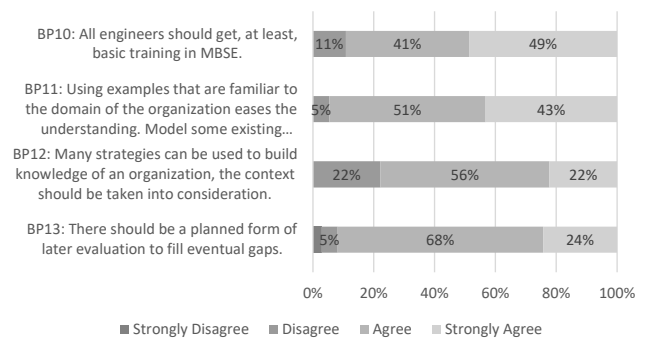


Fig. 6. Questionnaire results for Knowledge building group.⁹

relation can be achieved when deciding for tool adoption.

Related work. In the Jet Propulsion Laboratory of NASA [16], MBSE teams were organized in a 3-tier fashion, with a small set of core modelers, a larger set of modeling-savvy SEs, within larger set of project personnel. In this sort of team arrangement, everyone needs some sort of training, but not to the same depth. The authors of [2] cite three points that must be taken into account: (1) the existing process should be well documented and should cover the whole life-cycle otherwise is quite complicated to understand what needs to be adapted, (2) the MBSE model management processes (i.e., creation, update, and maintenance of models) should be defined thereto derive engineering artifacts, (3) investment in full-scale MBSE tool (i.e., not RE management tools) that are accessible to all team members is necessary. Whittle et al. [17] stress the importance of social and organizational factors for the selection and development of tools. They found in their study that it is better to “Match tools to people, not the other way around” and to “more focus on processes, less on tools”. The provided answers in our interviews reflect the opinion that exchange of information (i.e., models) between tools is a problem that must be addressed by proper import/export mechanisms and open interfaces. In a previous study, we have seen that tool incompatibility is one of the major forces that hinder companies to adopt MBSE solutions [3]. Research has developed alternatives that may fit the MBSE paradigm better. Seamless MBSE may be supported by multiple tools manipulating models in a common model repository instead of importing/exporting models (cf. *projectional editors* [18]).

D. Knowledge building

Training can be carried out in many ways. In this subsection we will present different views and strategies which sometimes can also be contradictory. This does not invalidate them as the reader should realize that the context of the organization influences the best approach. The questionnaire answers had a good agreement rate with the best practices, the smallest being 78% rate of ‘Agree’. The exception is BP12 which received 22% ‘Disagree’s. (cf. Figure 6).

⁸BP07 and BP09 received 3% of ‘Strongly Disagree’ each.

⁹BP13 received 3% of ‘Strongly Disagree’.

BP10: All engineers should get, at least, basic training in MBSE.

“Training, training, training!” (P1)

“Basic training for all users of MBSE” (P6)

“Everyone who uses MBSE should be trained in the methodology” (P8)

“Broad basic training of all employees - Everyone should have the same understanding” (P9)

Basic training should be provided to all employees. Nevertheless, the required knowledge will vary among team members (i.e., not everyone will require the same type of knowledge or in the same depth). For instance, developing complete models require much deeper knowledge than only understanding them.

BP11: Using examples that are familiar to the domain of the organization eases the understanding. Model some existing artifacts for using as examples.

“Examples from similar industry help” (P9)

“Catching up with experiences / feedback from the network (from the same industry)” (P13)

“[Training team] has modeled examples of clients and then presented them [sic] to the client (we’ll show you how we do it)” (P2)

The overall understanding can be enhanced by modeling some requirements that are familiar to the developers. The effort required to understand what is being modeled (i.e., domain) is diminished thus trainees can concentrate solely in the modeling concepts. If an organization has no prior knowledge in MBSE or modeling in general, it helps when some experts model small parts of existing systems from the organization as examples to transfer and demonstrate the idea of MBSE.

BP12: Many strategies can be used to build knowledge of an organization, the context should be taken into consideration.

“F2F, except perhaps for basics” (P6)

“Face-to-Face Seminar with exercises” (P7)

“Deeper training of individual employee, who then pass on their knowledge in the team” (P9)

Depending on the dynamics of the team, it is possible to concentrate the training on a small group of participants and later those people will be responsible to disseminate the knowledge in the bigger group. This strategy fits very

well when the piloting is performed also with a small part of the team. Other interviewee said that training should be done with face-to-face seminars followed by exercises. As we can see both approaches seem to work therefore the context should drive such type of decision.

“Per tool training e.g. Doors¹⁰” (P7)

“Model should be reference. To do this, connect other tools (e.g., importing Doors¹⁰ for initial filling, then only update exports back to Doors, generated code frames force interface fidelity)” (P5)

Tool and process are very intertwined in MBSE thus training should mind the tools that will be used. The training should have emphasis in the model, showing there should not be co-existing two artifacts with the same purpose, namely a document-based version and a model-based version. The verbatim above gives the example of a requirements modeling tool (Doors).

“Strategic cooperation, introductory consulting [...] Coaching during the introduction has proven very successful” (P1)

Hiring external consultancy to provide training guarantees a minimal homogeneous level of knowledge throughout all employees. Experienced consultants are very efficient and can transmit the knowledge very efficiently. However one should have in mind that participant P1 works with technical sales.

BP13: There should be a planned form of later evaluation to fill eventual gaps.

“Continuous explanation of the methodology” (P1)

“Accompanying technical monitoring of work results; is not happening systematically.” (P5)

Training is an ongoing process, which includes returning to training concepts at a further point in time and assessing the engineers’ knowledge (e.g., through the quality of the artifacts being produced). This is necessary to be put into practice and is not happening systematically.

Related work. The training activities should use real examples since they are much more effective at conveying understanding and building support [16]. According to [2], the organization should nurture a cadre of trained systems engineers with at least moderate skill in employing MBSE tools and techniques, and whose MBSE roles are clearly delineated from the more traditional roles. For the engineering staff a basic level of training in the MBSE processes (so that they understand the value of the models and what to expect from the systems engineers) and in how to read MBSE artifacts (so that they can interpret information provided from the MBSE processes). Although the awareness towards training, 62% of “MBSE active users” surveyed by [19] never received official training from their organization and just 2% had a complete technical course sponsored by their organization. In line with the reported best practices, several works exist that report on efficient transfer of MBSE methodologies by remodeling

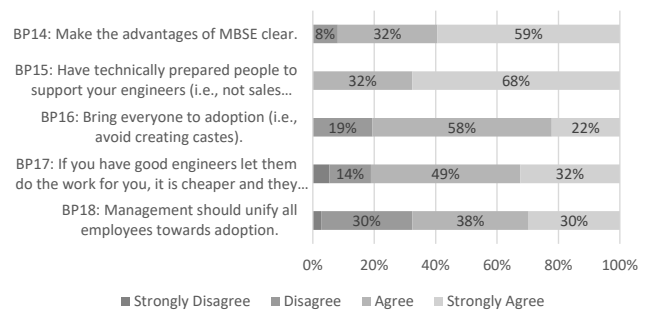


Fig. 7. Questionnaire results for Management group.¹¹

parts of existing systems from companies (e.g., [20]). Tool vendors usually provide training for the methodology and work-flow to be used with their own products [21].

E. Management

Although current state of the practice has achieved some degree of automatization in systems engineering, its tasks are still human-intensive. Thus, introducing process change in an already running and established organization is not frictionless [22]. In an ideal world everyone would jump in the adoption boat without hesitating and fully motivated, the reality says that management should care for the team vibe towards the adoption. Micromanagement is required to tackle hurdles and psychological barriers, specially when it comes to such a complex change as MBSE adoption [3]. This section is about strategies to manage the overall mood and expectations of the ones affected by MBSE adoption.

The questionnaire results showed that BP16, B17, and BP18 received many disagreement votes. Although most of the respondents still agreed with them (i.e., at least 68% of Agreement). One hypothesis is that they are context dependent. In the other hand, BP14 and BP15 got almost no disagreeing votes. (cf. Figure 7)

BP14: Make the advantages of MBSE clear.

“Advantages of simulability were made visible” (P11)

“Good examples show: project for new methods tools, then show that it works (utility and acceptance).” (P13)

“Representation as a means of unique selling proposition. Works, but each developer must be convinced individually.” (P10)

The way people perceive the MBSE introduction can become an obstacle, thus it is very important to manage the mood of those involved, especially in the very beginning, when everything is experimental. The advantages of the approach should be made clear, also emphasizing benefits for the employees. By doing so, organizations can foster engineers acceptance and collaboration towards MBSE adoption.

“Every few years new product generation, e.g. because of Platform changes through technical advances (multicore ...) or new system approaches that affect many functions. Then there is a break in the system concepts, many have to be

¹¹BP17 and BP18 received 5% and 2% respectively of ‘Strongly Disagree’ each.

¹⁰<https://www.ibm.com/us-en/marketplace/rational-doors>

taken in hand, because you can introduce new methods.” (P10)

As the technology evolves, new paradigms need to be adopted to keep up with the market. Pairing such changes with MBSE adoption improves its acceptance by surfing on the already needed change atmosphere. However, waiting for a paradigm shift may take a while, thus, this is very specific strategy and is not fit for all situations.

BP15: Have technically prepared people to support your engineers (i.e., not sales personnel).

“Tool sellers sometimes only send sales personnel, can not answer technical questions, does not make a good impression.” (P13)

The engineers will have very specific and technical doubts about the modeling environment. Therefore, having prepared people to support them is fundamental. Sales personnel are usually not enough prepared for this task and failing to do so might raise skepticism towards the adoption.

BP16: Bring everyone to adoption (i.e., avoid creating castes).

“Avoid living apart, everyone has to go!!!” (P9)

Other best practices enforced that all employees should receive access to the tools (BP07) as well as basic training (BP10). The problem of not doing so is the creation of two classes of engineers (i.e., those working with MBSE and those that aren’t) and this can jeopardize their motivation. Albeit, it is not uncommon teams working in different technologies in the same organization. Another exception is when the strategy is to train few engineers which will pass the knowledge to the others. This point should be considered with reservations.

BP17: If you have good engineers let them do the work for you, it is cheaper, and they will engage more (i.e., empowering).

“Information model developed itself” (P7)

“[The knowledge was created by the] developers available or self-built (i.e. only UML and the DSLs)” (P4)

Some organizations had their developers learning about models on their own (i.e., the knowledge was organically developed). That is not so surprising since in technological areas engineers need to be learning new technologies all the time.

BP18: Management should unify all employees towards adoption.

“Guidance from management important to bring everyone on the same platform” (P6)

Implementing MBSE involves engineers from different phases of the software development and from different fields of engineering. These professionals are usually not working together in an everyday basis. Filling this gap is the duty of management, thus uniting the whole team towards MBSE adoption.

Related work. In a previous work [3], we identified forces that work towards *hindering* or *fostering* the adoption of MBSE and their origin. Hindering forces can be classified

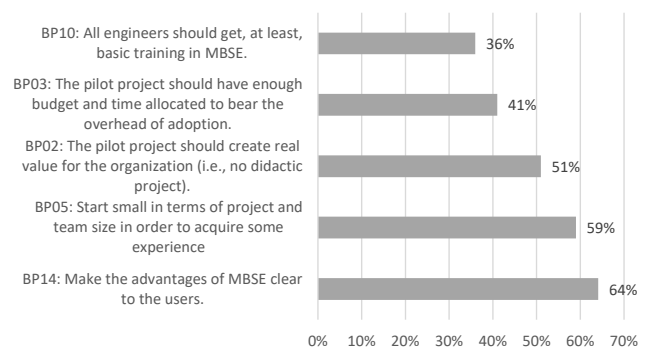


Fig. 8. Top-5 most important best practices given by the percentage of respondents that have rated them as “most important”.

as either Inertia or Anxiety. The former is triggered by the feeling that the current solution is “good enough” and habits that keep people from trying out something new. The latter is triggered by fears that MBSE adoption will not pay-off, mainly caused by uncertainties and perception flaws [3]. Motamedian [19] had in his survey questioned subjects about barriers using MBSE. The second and third reasons most voted were “the lack of perceived value of MBSE” and “resistance to change”, therefore the need to micromanage the engineers expectations and motivation toward the process of adoption. Some ideas are just normal process changing measures with MBSE flavor. This was something also found by Hutchinson et al. [4] Nevertheless, the emphasis and alignment with other phenomena increase their relevance thus are worth mentioning. The challenges that arise [3] are due to the nature of the current context, the shift to MBSE (e.g., compile development skills vs abstraction skills), and the human-in-the-loop.

F. Most Important Best Practices

Besides validating our interview findings, we used the questionnaire to discover which best practices are considered the most important. For this means, we asked the respondents to select among all BPs the five most important when adopting MBSE. The results can be seen in Fig. 8. From the 5 most important, three were from the Piloting group, one from the Knowledge building group and the most voted is from the Management group. The BPs are discussed in the following under this light:

BP14 The most important BP is related to increasing the engineers’ motivation towards MBSE adoption by making them understand its benefits. Engineers are less likely to withstand the hurdles of adoption if they cannot perceive its benefits [3]. Systems Engineering is a human-intensive activity thus the collaboration of the engineers is crucial for adoption success.

BP05 is about using a small setting to understand the best way to introduce MBSE considering the organization context. Through experimenting, managers can understand which tools, languages, and styles are best fitted for the organization and its respective domains and current processes.

BP02 is about making the adoption efforts meaningful and relevant right from the beginning. By working into something that will be used in production setting, the employees have to learn and employ MBSE. If it is something that is just for learning, there are no consequences if the project is incomplete or not well done thus making the learning also incomplete. It also gives room for procrastination (i.e., learning later when it is necessary).

BP03 This BP relates to the effort required by the engineers to develop their MBSE skills. The project selected to pilot the adoption should have its budget planned to cover the learning curve costs as well as the delivery of its artifacts should be planned accordingly. Time-critical projects should be avoided. If the project selected is not fit, the engineers will drop the MBSE techniques in favor of already established development methods in order to achieve celerity gains and meet deadlines. The adoption is very likely to fail.

BP10 In a system project, different skill sets are mastered by different professionals which specialize in specific parts of the life-cycle (e.g., development, testing, design). Despite their skill focus, all professionals have an overall system development knowledge which helps them to understand the big picture. This is similar to what should happen with MBSE. Although not all engineers require deep modeling skills, everyone should be able to, at least, read and understand the models.

As for the least important best practices, *BP04: No translation of old artifacts except for reusable artifacts* was not selected as “most important” by any of the respondents. *BP12: Many strategies can be used to build knowledge of an organization, the context should be taken into consideration* was selected only once.

IV. RELATED WORK

In this section, we list and comment on similar studies. The intersections with each of our findings are discussed in detail in Section III.

Motamedian [19] reports on an on-line survey among MBSE practitioners. The author’s goals were: (1) to highlight the position of MBSE in real projects, (2) to assess the popularity rate of MBSE concept among engineers, and (3) the usage besides the advantages (i.e., barriers and concerns of using “modeling language” and “modeling tools”) in MBSE efforts among various industries. In an MBSE workshop, the lessons learned while implementing MBSE at the Jet Propulsion Laboratory of the American National Space Agency (NASA) and the Mars2020 project [16] were presented. Carroll and Marlins [2] describe the benefits of MBSE adoption extracted from a series of case studies. In the end of the study, the authors present a list of implementation-lessons drawn from the findings. For them, the cultural changes necessary to implement an MBSE approach successfully (roles, rewards, behavior, and support at all levels) were described as the most difficult challenges to overcome. In a previous study [3], we identified forces that foster or hinder MBSE adoption in practice. The focus

TABLE III
HUTCHINSON’S RESPONSES AND RELATED BEST PRACTICES

| Response | Best Practice |
|--------------|------------------------|
| Adaptive | BP14, BP16, BP17 |
| Business led | - |
| Committed | BP03, BP07, BP10, BP18 |
| Iterative | BP05 |
| Progressive | BP05 |

was on listing characteristics without analyzing possible solutions.

A. Hutchinson et al.

Hutchinson et al. published a number of papers that focus on adoption of Model Driven Engineering (MDE) in the context of software development [4], [17], [23]–[25]. Their research comprise case studies built around semi-structured interviews and on-line surveys devised to gather information about MDE usage through closed questions (e.g., diagrams used for modeling, modeling languages, MDE purpose of use, etc). In [4], their findings are summarized into 10 dimensions of organizational attitude to MDE adoption, half being helpful responses and the other half being unhelpful. The responses are described in a very broad and general manner. Table III provides the relation between their helpful responses and the best practices describe by us. In [24], [25], the authors state that MDE should be tried on projects that ‘can not fail’. We also reported similar finding as presented by BP02. In [17], they present a taxonomy of MDE tool related issues; ‘Chaining tools together’ and ‘Flexibility of tools’ are covered by BP06, ‘Sustainability of tools over the long term’ and ‘How to select tools’ are related to BP08. Albeit the intersection of our findings with the work of the aforementioned authors, our contribution goes further:

- Their focus was MDE (a software development methodology which encompasses models and code generation) whilst our focus is on MBSE (a systems engineering methodology devised for covering mechatronic, electronic and software parts). MDE is a subset of MBSE (i.e., $MDE \subseteq MBSE$).
- Their case study findings are based on anecdotal evidence, whilst we used questionnaires to empirically validate and generalize our conclusions with practitioners in a triangulation [6] fashion (i.e., the questionnaire was built based on the conclusions we derived from the interviews (cf. Section II)).
- Their findings are laid out within discussions of case studies whilst we provide a crisp list of best practices and a prioritized list of the five most important ones, aiming to help practitioners to know where to focus.

V. CONCLUSIONS AND FUTURE WORK

The complexity of MBSE and its pervasiveness creates challenges that when not properly addressed can jeopardize its implementation in an organization. In this work, we identified best practices of MBSE adoption through a series of interviews. These practices were then classified in four big groups: piloting, knowledge building, tools and process, and management. Further, they were discussed, compared

with related work, and summarized at the end of each group subsection. These summaries were used to build a questionnaire in which each respondent could express their level of agreement with the best practice.

Adopting MBSE is no trivial task. However, companies are gaining experience in MBSE adoption and there are success stories as well [26]. There is no need to reinvent the wheel, thus learning from the experience of others and applying proven best practices can save effort and enhance the chances of success. In the long run, benefits outweigh the costs and hurdles, however, it is necessary to identify success factors and share best practices enabling efficient and effective MBSE adoption in industry.

As future work, we could investigate the Best Practices that received many disagreement votes to understand whether context plays a role in such phenomenon.

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