Questioning integration of verification in model-based systems engineering: an industrial perspective

Christopher Laing, Pierre David, Eric Blanco, X. Dorel

Version of Record: https://www.sciencedirect.com/science/article/pii/S0166361519302799
Manuscript_de82f6116e617f53741ceeba776e50fc

QUESTIONING INTEGRATION OF VERIFICATION IN MODEL-BASED SYSTEMS ENGINEERING: AN INDUSTRIAL PERSPECTIVE[1]

C. LAING, P. DAVID*, E. BLANCO

Univ. Grenoble Alpes, CNRS, G-SCOP
38 000 Grenoble, France
christopher.laing@outlook.com, pierre.david@grenoble-inp.fr, eric.blanco@grenoble-inp.fr
* corresponding author

X. DOREL

Schneider Electric
38000 Grenoble, France
xavier.dorel@schneider-electric.com

[1] This article is an extended version of Laing, C., David, P., Blanco, E., & Dorel, X. (2018, June). Questioning integration of verification in model-based systems engineering: an industrial perspective. In *MOSIM'18*.

QUESTIONING INTEGRATION OF VERIFICATION IN MODEL-BASED SYSTEMS ENGINEERING: AN INDUSTRIAL PERSPECTIVE[1]

[1] This article is an extended version of Laing, C., David, P., Blanco, E., & Dorel, X. (2018, June). Questioning integration of verification in model-based systems engineering: an industrial perspective. In *MOSIM'18*.

ABSTRACT: *The increasing of complexity of industrial products makes Verification and Validation procedures challenging. Model-Based Systems Engineering (MBSE) has been proposed as an approach to manage such complexity through the formalized application of models throughout the systems development life cycle to support verification activities.*
The purpose of this paper is to make a first step towards developing a verification strategy by performing a qualitative survey on current industrial practices against the state of the art in MBSE.
Data had been collected through workshops of 16 engineering organizations located in the Rhone-Alpes region of France. Key success criteria for integrating model-based verification with MBSE are identified by industry respondent. These criteria allow to analyse the top verification methods presented in MBSE publications and compare them to current practices. To further validate the use of these presented methods, interviews and observations were conducted to analyse the methods through different industrial perspectives and identify their feasibility for successful application. The findings of this study gives a picture of current practices in integrating verification and MBSE in industry. The paper discusses the impact of implementing such practices in companies beginning to adopt MBSE approaches. It is concluded by identifying opportunities and barriers for Model-Based Verification adoption.

KEYWORDS: *Model Based Systems Engineering, Verification, Industrial practices, Survey*

1 INTRODUCTION

With the growth of complexity in modern products, the use of the systems engineering (SE) approach has spread across many industries. To manage products development, systems engineers need to handle considerable amounts of information regarding the requirements, interfaces, verification plans and system description throughout the system development life cycle. To overcome difficulties to maintain and synchronize this data scattered across many documents and standards, Model-Based Systems Engineering (MBSE) has been developed to enhance the ability to capture such information through the use of models (INCOSE, 2015). But a recent workshop organised by INCOSE reported a lack of MBSE benchmarking and sharing of practices (White & Mesmer, 2019). This paper expect to contribute to this experience sharing.

The use of models offers new opportunities to verify engineering data through model analysis and execution. The potential to increase verification through model-based techniques has been a key initiative in the last decade (NDIA, 2011), challenging both systems and model-based engineering communities. Despite specialized domain or discipline techniques being developed in isolated pockets, much work is left to be done considering the virtual verification of models representing the integration of multiple domains, disciplines, and subsystems to analyse performance on a system level. This early virtual or digital verification has been recognized as a key objective to meet the demands of current industrial product development (Maropoulos & Ceglarek, 2010). Interest has been growing towards the combined use of MBSE and digital verification to reduce errors being discovered lately in projects (Frank, et al., 2016). However, the transition to MBSE is not a simple process as it involves changing from legacy practices relying on documentation not only in the organization but also in the organization's network of suppliers and clients (Friedenthal et al., 2014).

Despite the new verification opportunities provided by MBSE, cost, time and organizational constraints make it infeasible to model and verify every element in the design of a complex system. A verification strategy must be drawn which incorporates various verification techniques to reduce risk in projects while controlling the resources to perform verification. As a precursor to developing such a strategy, this research seeks to identify model-based verification techniques applicable to systems engineering projects. More important than identification, it should be determined what are the impacts of these techniques and what restrictions are faced when being implemented in real projects. To make this assessment, the current state of model-based methods in SE should be determined to identify possible opportunities and restrictions to the development of a global verification approach based on model-based techniques. For this purpose, this study has been carried out to answer the following Research questions:

RQ1. What are the desired benefits of model-based verification for companies adopting MBSE?
RQ2. What model-based verification methods may be used to obtain these benefits in an MBSE approach?
RQ3. What restrictions, both technical and organizational, impacts the efficiency of MBSE verification in real projects?
RQ4. What are the differences between the published results of applying verification in an MBSE framework compared to the results of a broader SE community?
RQ5. Why do these gaps exist and what opportunities are available to improve the verification outcomes of the model-based techniques currently in use?

To tackle these questions, a qualitative study had been proposed in the Rhône-Alpes region of France thanks to the INCOSE French chapter (AFIS). Each organization, despite coming from different sectors, utilizes SE principles to manage the complexity of their project development. Section 2 introduces related works on the definition of model

based verification and on studies of practices in MBSE. In the third section, the research design of the qualitative study is presented. Section 4 focus on review of literature on MBSE verification technique realized as base of workshop interactions with experts. Section 5 gives the first workshop output as a list of success criteria for deployment of Model-Based Verification techniques. Section 6 reports on the analysis of industrial practices and their feedbacks on the explored state of the art. Section 7 and 8 conclude the paper by discussing obtained results and by providing research directions.

2 RELATED WORKS

2.1 Model-based verification

Model-based verification refers to the verification of engineering data in the form of a model. There exist three general types of verification for such data – semantic review, testing, and formal methods (Douglass, 2015).

- Verification by semantic review

A semantic model is "A chart or diagram, having an underlying machine-readable representation, which shows object relationships, structure, or time sequencing of actions" (Baker et al., 1996). SysML Activity and Block Definition Diagrams may be given as examples.

Review of a semantic diagram is the verification by inspection that utilizes human reasoning accompanied by simple methods of measurement to judge correctness (INCOSE, 2015). It includes solving a static analytical model. Unfortunately, the semantic review is often limited to verify that models are built the right way but it does not guarantee they model the right thing.

- Verification by testing

Testing is verification through the execution of a model. For testing to occur, a model must be created in an executable form for a dynamic analysis study of how outputs of the system vary over time from the expected results. Testing requires a test case including a specified environment, inputs, initial conditions and all actions that must occur for the requirement under study to be verified. Testing is limited compared to formal methods in that it seeks to discover errors but does not prove that errors do not exist (Schamai, 2013). Simulation is a type of testing where the focus is on placing the model in a specific environment and replication of real system behaviour.

- Verification by formal methods

Formal techniques show correctness of a model through mathematical proofs. They are comprehensive verification methods as the verification result holds for any combination of inputs or system states; however, the difficulty of performing the techniques typically limits them to critical system properties (Douglass, 2015). A formal method seen in MBSE is *model checking* where numeric or symbolic computation is used to show that a system property holds for every possible system state. The technique is limited to system models with a limited number of states, due to the fact that in a complex system it may be impossible to analyse every possible execution in its entire state space (Schamai, 2013). Chapurlat claims in (Chapurlat, 2013) that INCOSE essentially promotes formal or non-formal techniques whether formal techniques could bring many advantages for verification as improving exhaustiveness, traceability and automation of the proof process.

2.2 MBSE practices studies

Yet MBSE adoption remain limited, as it constitutes change in design organizations and practices. Recent discussions within INCOSE community reported a lack of sharing of practices (White & Mesmer, 2019). Thus related works that adress industry state of practices exists on the broader context of SE, MBSE and testing. For example, a recent qualitative study (Vogelsang, 2017) based on 20 interviews from 10 companies discussed the MBSE adoption drivers and barriers within German embedded system industry. Performing early verification appears to be one of the factor that encourage MBSE adoption. Huldt et al (2018) find similar results on factors that encourage or prevent the adoption of MBSE in their survey based on questionnaires. In 2012, Fanmuy and Foughali (Fanmuy & Foughali, 2012), utilized online questionnaires and interviews to analyze industrial practices in requirements engineering. The study is started by interviews at 8 companies with 14 individuals, and completed by an online survey within a working group of INCOSE on requirements management with 16 responses. The online survey were used to corroborate the interview results. They found that only a quarter of their interviewed companies were performing some model based verification and validation but the idea of using models was seen to be a high value added value practice. Another recent paper focuses on SyML usage in Germany and Austria. The panel of interviewees is jointly composed of engineers from industry and academia (Albers & Zingel 2013). They namely showed that MBSE formalism can provide help to tackle the communication difficulties between experts of different disciplines.

Previous studies in the field of computer sciences are also using qualitative survey through relatively small panels. Questionnaires, focus groups, interviews about MBSE practices are performed to highlight practices in the domain of requirement engineering (Weidenhaupt et al 1998; Neill et al 2003) or in software testing (Andersson 2002, Runesson

2002, Engtröm 2010). These last three studies are conducted by the same Swedish research group. Test automation appears to be an expected outcomes of MBSE in this context of Software engineering. But sometimes practices are relying on individuals more than processes. Yet some good practices on software regression testing are identified.
Fianaly other types of qualitative studies relate experiences of MBSE application. Case studies of using MBSE as experimental or learning by doing approaches are reported. These researches highlight difficulties and advantages of using MBSE in pilot project. Böhm et al. (2014) report an experiment in a railway project on transfer of knowledge from research results modeling approach. Gought et al (2018) shared lesson learned from project in the NASA environment. Bransen et al (2017) present an original use of MBSE in organization design within which models are used to inform workforce decisions relating to organization design, resourcing and training. Do et al. (2014) investigates MBSE practices across contractual boundary for requirement sharing. They pointed out the necessity to manage confidentiality in model sharing and the opportunity to share design rationale through models. Configuration management of model appears to be a challenge to address within this collaboration. These practical approaches often highlight difficulties and value added of the use of MBSE in the projects but are limited to one experience. Authors and researchers are often part of the engineering teams, reflecting advance used of MBSE but not general state of the art practices in industry.

3 RESEARCH DESIGN

3.1 A qualitative survey

Since the objective of the study is to better understand design practices within industry, empirical research is required. Thus qualitative or quantitative research are possible. Operation Management research (Rungtusanatham 2003) often relies on quantitative survey which are appropriate to theory testing, when research aim to confirm or validate model in focused research question. When larger questions are researched and oriented in theory building, qualitative research or what Robson and McCartan (Robson and McCartan 2016) call Flexible design of research is often used. The nature of the addressed research questions RQ1-5 leads us to adopt a qualitative approach, as it was done for most of work mentioned in section 2.2. Within Engineering Design academic community, DRM (Blessing & Chakrabarti, 2009) has been proposed as a framework to design the research which are using qualitative and empirical research about design activity. In our case, the type 1 research framework from (Blessing & Chakrabarti, 2009) is preferred since an exploratory study is necessary. An initial descriptive study had been based on literature survey and a qualitative survey involving practitioners. Thanks to intimate industrial partnership with one of the company, it would have been possible to carry out a case study analysis yet it seemed to be more interesting to cross different companies' perspectives to enlarge the vision. A quantitative survey was considered as a digital survey, but the number of potential answers for a digital survey would have been critical for this exploratory research. Yet MBSE application is not so well diffused in industry. As mentioned by (Huldt & Stenius 2018; Albers2013), definition of MBSE is not so stabilised and commonly shared. Thus a digital questionnaire would have generate biases of understanding difficult to track and handle. Thus a qualitative survey following DRM framework had been designed. Similar qualitative study had been realized by Andersson and Runeson (2002, 2003) in software engineering domain about testing, verification and validation. The following section presents the procedure followed.

3.2 Procedure

This research was conducted in different steps for collecting and treating data.

1. A community workshop to identify success criteria of Model Based V&V was organised with SE experts.
2. A State of the art was realized about Model based Verification techniques.
3. A second workshop with Experts allow to compare and discuss expert practices to these identified techniques.
4. Companies were chosen to deepen analysis with semi-structured interviews of experts.
5. A final analysis was proposed by researchers.

During the first workshop, definition of MBSE was discussed to align participant understanding of the concepts under study. Case study were presented by pratitionners to share experience and illustrate their practices on specific projects. Finally, a list of 10 needs concerning the deployment of verification within an MBSE framework were produced through a brainstorming and consensus definition session.
A second workshop was conducted three months later to present the state of the art of model-based verification techniques (classified in Section 4). The companies were presented the techniques following the Vee model and asked to comment on the practicality of each. They were also proposed to give complementing or opposing experiences. This information was captured in a handout given to each attendee. At the end of the workshop, an opportunity was given for the participants to suggest any additional techniques they have implemented. This second workshop included 10 organizations and 20 individuals (see table 1).

From their inputs during the second workshop, four organizations (respectively identified 6, 12, 13, 14 in table 1) were selected for a more detailed study. The organizations, except for one organization (6 in table 1), were interviewed over the course of 1 month. The data collected included a survey filled during the second workshop, a follow-up email questionnaire tailored to their experiences, a semi-structured interview ranging from 1 to 2 hours, and follow up email questions for answers clarification and validation.
An extended case study investigation was conducted in organization 6 which was the host company for this research. The data collection in Organization 6 was conducted in a structured approach over a 4-months span. 5 functions were chosen for interview - System Architects, System Engineers, System Modelers, and Domain and Verification Engineers. All interviews were conducted in at least two phases, first to understand how model-based verification is utilized in current practices and secondly to focus on how model-based techniques could answer to the identified criteria. A total of 18 interviews were conducted with 7 different individuals. Among them were 2 Domain Engineers, 1 System Architect, 2 Systems Engineers and 1 Systems Verification Engineer.

3.3 Surveyed Panel

The study was carried out with the support of the Rhône-Alpes chapter (CRRA) of AFIS which is the French chapter of INCOSE. The AFIS CRRA regroup several organizations producing services and products. Companies were invited to workshops promoted on the topic of Application of MBSE in Verification and Validation. Table 1 lists the 16 consulted organizations and marks their participation in the two workshops. Except from three organizations that were research organization (classify as academics in table 1), all organizations are private companies. The profile of attendees are presented in the Expert Profile column. Companies' Business model is also proposed since principal project organization can have an impact on processes. 'Market' refers to companies that address BtoB or BtoC markets or "contract" refers to companies which engineering work is mainly based on contracts given by customer. This can have an impact in the way that verification and Validation are performed. Nevertheless, at the state of the study it is difficult to observe the impact of this variable. Different size of companies had been encountered in the panel from large companies to start-up. The type of companies is given in year of existence and number of employees. They allow to differentiate well established or newly setup companies. It is also important to notice that some of companies are consultancy companies that provide engineering services to their industrial customers.
The initial workshop was held with 11 organizations and 22 participants. The represented industries may be seen in Table 1. The heterogeneity of the domains demonstrates the broad interest in MBSE verification. Similar Panel had been used in studies. The participant set obtained can be compared to a recent survey made on MBSE practices in (Huldt & Stenius, 2018). The population they evaluated is composed primarily of the US Aerospace & Defence industry (more than 70% of their respondents). The study present answers from the French community, which represents only 2% of the study by Huldt and Stenius. Albers et al (2013) present German and Austria experts' perception on MBSE. This study is thus complementing the vision of practices in EU. The industrial domains of the respondents is also interesting as this research covers industrial domains poorly captured in the Huldt & Stenius survey (e.g. Medical Industry and Electronics Industry). The two surveys were conducted in comparable periods and thus give complementary visions on industrial practices in MBSE.

ID	Industrial Sector	1 WS	2 WS	Expert Profile	#Employees	Business model	Age
1	Civil nuclear services firm	X	X	Head of Engineering Means	>50000	Contract	>20
2	Research Industrial engineering A	X	X	Researcher	NA	Academic	
3	Research Industrial engineering B	X		Researcher	NA	Academic	
4	Software and embedded system consultancy A	X		Consultant	20-50	Contract	10
5	Software and embedded system consultancy B	X	X	Sofware Engineer	250-500	Contract	5
6	Electronics design and manufacturer A	X	X	System Architect	45000	Market	>20
7	Electric Equipment manufacturer B	X	X	System and Software Engineering Manager	142000	Market	>20
8	Defence systems design and manufacturer	X		System Engineer	3300	Contract	>20
9	Medical instruments firm A	X		System Engineer	11200	Market	>20

10	Software solutions provider	X		Not given by participant	Unknown	Unknown	unknown
11	Engineering simulation firm	X		Software Engineer	250-500	Market	>20
12	Medical instruments firm B		X	Design Quality & Performance Manager	250-500	Market	>20
13	System modelling software organization		X	Expert MBSE	>16000	Academic	
14	Software and embedded system consultancy C		X	Embedded Software Engineer	>11000	Contract	>20
15	Electronics design and manufacturer C		X	System Engineer	10-19	Market	5
16	Medical instruments firm C		X	System Architect	10-19	Market	<5

Table 1. Workshops panel composition (WS)

3.4 Trustworthiness

Trustworthiness is questioned as soon as qualitative study is performed, since classical criteria of external, internal or construct validity of quantitative research cannot be applied (Le Dain et al 2013). Different dimensions of trustworthiness are *credibility, dependability, transferability and confirmability*. Different techniques were used to prevent biases in the study (Robson 2016) and address *credibility* and *dependability* which are close to internal validity. *Credibility* elements are given in the structure of the study. The panel description (table 1) shows diversity of data sources. Peer debriefing was used since three different researchers where committed. Interviews and data collection were performed by principal researcher, Data treatment and analysis had been jointly realized by two of the authors allowing to cross perspectives and interpretation. Third authors were used as external reviewer for quality assessment of analysis which address also *dependability*. *Member checking* was used asking respondent to give systematic feedback on analysis proposed by researchers when it was possible. It was systematic in the semi structured interview process. *Triangulation* was also performed through document analysis within companies or questions crossing (direct and indirect). *Transferability* is linked to external validity and research generalization. Diversity of companies is a partial answer, yet study is limited to practices in French region and the panel remains small so claiming of genericity has to be limited. Finally, *confirmability* deals with construct validity. In other words, does the study really address what is intended to show? Participation and review from system engineer expert of one company, principal researcher *prolonged involvement* within company and mixing of workshop data collection and deeper semi-structured interview were used to guarantee confirmability. In summary, the approach used different techniques and procedures available in literature to prevent respondent and researcher bias in a structured process of qualitative research. Rigorous data collection and data treatment were used to guarantee trustworthiness of the results.

4 STATE OF THE ART OF VERIFICATION INTEGRATED WITH MBSE

To prepare the second workshop, a review on the model-based verification literature focusing on the design and development activities has been performed. To remain close to the background knowledge of the participant companies, the literature presented was pulled from INCOSE publications between 2010-2017 by searching with combinations of the key words “model”, “based”, “verification” and “virtual verification”. Papers were selected on the basis that they presented verification activities using models within an MBSE context. The INCOSE corpus was selected, as it is a major international organization recognized as the reference in SE.

The review includes relevant secondary sources from the INCOSE publications, primarily references to the journals of IEEE, ITEA, the conference Models and work presented by groups such as NASA, JPL, the Computer and Information Sciences department of Linköping University, and the John Hopkins University Applied Physics Laboratory. This review presents the process and the methods of verification activities without prejudice to the modelling language or MBSE methodology applied. It is not claiming to be exhaustive, but it aims at referencing the works accessible to the contacted companies.

Table 2 shows a summary of the identified techniques from literature organized by their application in the traditional SE technical processes. The first column gives an identifier for the kind of technique. Initials of the process phases are used to identify the techniques. The second column shows the process in which the techniques may be applied (according to the technical processes of IEC 15288). Column 3 gives the verification type and column 4 the type of model. Column 5 gives the targeted element for verification. For the complete review, the reader may consult (Laing, 2017). Relevant papers are cited in column 6 and reviewed is section 6.

Identifier	Process	Verification Type	Model Type	Verified Element	Paper example
V-BA.1	Business or mission analysis	Semantic review	Semantic diagrams	Completeness of problem space	(Kass & Kolozs, 2016)
V-Stk.1	Stakeholder needs and requirements definition process	Semantic review	Behaviour diagram	Stakeholder and needs identification completeness	(Waite & Logan, 2011), (Favaro et al., 2012)
V-SR.1	System requirements definition process	Semantic review	Requirement diagram	Completeness of system requirements or rational for omitting certain needs	(Kass & Kolozs, 2016)
V-SR.2		Testing	Executable form of semantic diagram(s)	System requirement specification	(Shokry & Hinchey, 2009)
V-SR.3		Formal - Model Checking	Executable form of semantic diagram(s)	System requirement specification	(Seidner, Lerat, & Roux, 2010), (Schamaï, 2013)
V-FA.1	Architecture definition process – Functional and Logical	Semantic review	Semantic architecture	System architecture quality	(Carson & Kohl, 2013)
V-FA.2		Semantic review	Requirement diagram	Requirement traceability	(Caron, 2012), (Kass & Kolozs, 2016)
V-FA.3		Testing	Executable form of semantic diagram(s)	System requirement specification	(Gopinathan, et al., 2012)
V-FA.4		Formal - Model checking	Executable form of semantic diagram(s)	System requirement specification	(Pétin et al., 2010)
V-FA.5		Formal – Ontology	Semantic architecture	System architecture correctness	(Favaro et al., 2012) (Wagner et al., 2012)
V-PA.1	Architecture definition process – Physical	Semantic review	Requirement diagram	Requirement traceability	(Caron, 2012)
V-PA.2		Semantic review	Parametric diagram	Requirement specification	(Bjorkman et al., 2013)
V-DD.1	Design Definition Process	Testing	Multiphysics system model	System requirement specification	(Caron, 2012)
V-DD.2		Testing	Multiphysics system model	System requirements	(Schamaï, 2013)
V-DD.3		Review (3D model)	Discipline simulation model	System requirement specification	(Bajaj et al., 2011)
V-DD.4		Testing	Discipline simulation model	System requirement specification	(Bajaj et al., 2011)

Table 2. Summary of verification techniques found in the literature

5 SUCCESS CRITERIA FOR VERIFICATION IN MBSE

The first expert workshop allowed to identify success criteria for introducing Model-Based verification techniques. Each success criteria may be seen as a need showing how models must be used to improve verification, both early in design and in the final verification stages. The criteria list has been obtained through a brainstorming and consensus creation working session. It clearly reveals the industrial panel thoughts on the addressed topic. The criteria and their explanations are listed below:

C1. Reuse of models
Reuse of models deals with the ability to reuse the modelling efforts required to perform a verification technique. These efforts may be reused in future projects or later within the same one.

C2. Completeness of verification
Completeness of verification deals with the ability of the techniques to increase coverage above the level offered by the document based systems engineering approach.

C3. Test automation
Test automation relates to the ability to use the model-based techniques to automate verification.

C4. Collaboration and exchange tool
Collaboration and exchange refers to the ability of the technique to foster collaboration between parties using different tools or in different disciplines.

C5. Coherence between abstraction levels
Coherence between abstraction levels deals with the ability of the technique to be applied at one abstraction level effectively without the complexity of incorporating multiple system and abstraction levels.

C6. Detection & anticipation of problems
Detection and anticipation of problems deals with the technique's ability to find errors within the system due to changes or regular iterations of the system design.

C7. Verification of specification
Verification of specification refers to the ability of the technique to verify a requirement specification early in the project before physical prototypes of the system are implemented.

C8. Reduction of verification overlaps
Reduce instances of work being verified multiple times at different project steps or abstraction levels.

C9. Master modelling efforts
Minimize the cost and effort of modelling while still receiving benefits from MBSE.

C10. Mastering verification of complex systems
Reducing the number of errors discovered in implementation, integration, verification and in the field.

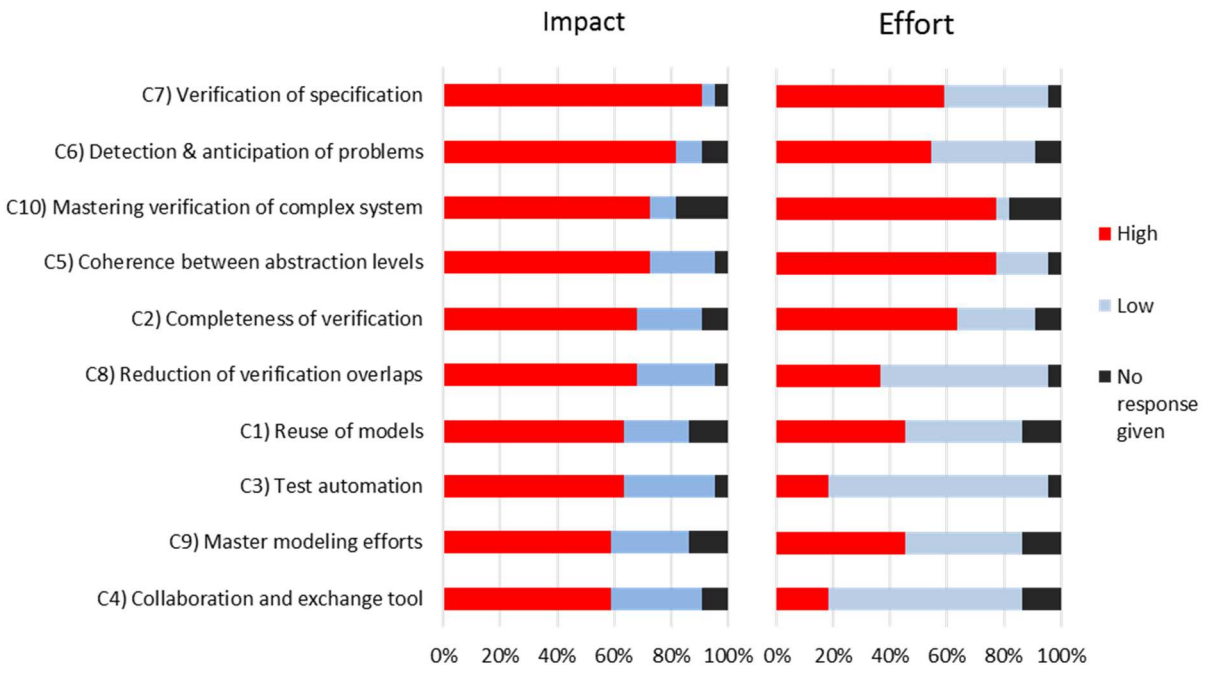

Figure 1: Success criteria evaluation by participant companies

These criteria are the expectations of companies when deploying MBSE practices for the V&V activities. Some are expressing expected new verification capabilities (C3, C7). Some are expectations to master the V&V process (C2, C4, C5, C6, C8, C10) or to master new challenges brought by the use of models (C1, C9). With this feedback, it can be assumed that practitioners are firstly expecting a better management of their current operations through the use of MBSE practices. Their expectations on the process are more or less synthetized in C10 which is about mastering the complexity of system development. The classic facets of complexity mastering are represented: abstraction manage-

ment C5, anticipation C6, completeness C2, collaboration C4 and optimization of engineering effort C8. The criteria C1 and C9 demonstrate that practitioners are aware of the inherent impediments of the transition to Model-Based approaches in organizations (time consuming modelling effort, mastering reuse of created models/data). The panel judges their avoidance as prerequisites for deploying such an approach. This analysis gives a complementary vision to the work of (Huldt & Stenius 2018) that analysed the level of satisfaction and inhibitors to MBSE adoption and not the motivation of companies. This criteria elicitation gives us a clear view of a company's motivation in setting up MBSE approaches (namely for V&V activities). The criteria given may also be compared to the criteria revealed in (Quintana et al. 2010) dedicated to Model-Based adoption for mechanical drawings. Their study pushed 5 distinct criteria: Data Integrity, Openness Adoption, Interoperability, Security and File Size. Interoperability and openness are recognized by our corpus through C4, but security and data aspects are not seen as big challenges in our study.
To better understand the perceived benefits of obtaining each criteria, the AFIS community was asked to rank each criteria by the effort required for their implementation and their possible impact on the project. In this way, each need could be labelled by the community as needing a low or high effort to be implemented and as having a low or high positive impact on the verification in the project. The response of the participants is shown in Figure 1 as a percentage of 22 individuals. A first comment is that almost every criterion is viewed as having a high impact on the verification process, showing that model-based verification raises many expectations from practitioners and that its adoption would be dependent on its success in many aspects. This imposes constraints on deployed techniques to be efficient in multiple dimensions such as mastering modelling effort and reuse while supporting communication and new problem detection.

Concerning the perceived effort to reach each success criteria, a consensus is difficult to obtain. Depending on the experience of companies, the visions are often very different. The ninth criteria, "mastering modelling effort", highlights this discrepancy as the participating companies were split equally between the two possible responses.

6 MODEL-BASED VERIFICATION IN MBSE FROM AN INDUSTRIAL PERSPECTIVE

The analysis of industrial practices was conducted in two phases. The first being the second part of the first workshop where participants were asked to describe their verification techniques throughout the SE process. Then during a second workshop, participants were asked to share their experience with techniques identified in the state of the art shown in Table 2. This process was organized to first capture their practice and then their feedbacks on the available techniques.

6.1 Currently observed practices

In the first workshop, 21 total techniques were collected as shown in Table 3. In Table 3 verification target, method, phase of use and impact on the project are detailed. While nearly 90% of non-model-based methods were identified as having an impact on the project, the impact of model-based methods was declared by participants for only 25% of techniques. The connection between these techniques and an MBSE approach is not captured, meaning that many of these techniques may be related to model-based engineering without sharing the paradigm of MBSE. This mainly shows that current practitioners have difficulties to evaluate the impact of their Model-Based verification actions compared to non-Model-based ones. This might be because for the majority of the participant companies, MBSE verification techniques are mostly deployed on pilot projects.

N°	Model-Based?	Verified Element	SE phase	Technique	Impact on Project
1	No	Stakeholder needs	Stakeholders needs definition	Review	High
2	Yes	Behavioural specification	Stakeholders needs definition	Test	Unknown
3	Yes	Stakeholder needs	Stakeholders needs definition	Review	Unknown
4	No	Stakeholder needs	System requirements definition	Unknown	High
5	Yes	Behavioural specification	System requirements definition	Simulation	Redesign
6	Yes	Behavioural specification	System requirements definition	Simulation	Go/No Go
7	No	Behavioural specification	System requirements definition Functional Architecture	Review	Unknown
8	No	Requirement traceability	System requirements definition Functional Architecture	Review	Medium
9	Yes	Requirement traceability	Integration	Review	Unknown
10	Yes	Requirement traceability	Functional Architecture	Review	Unknown
11	Yes	Behavioural specification	Functional Architecture	Test	Unknown
12	Yes	Requirements	Functional Architecture Physical architecture & detailed design	Review	Unknown
13	Yes	System requirements	Functional Architecture Physical architecture & detailed design	Simulation	Go/No Go
14	No	Performance requirements	Physical architecture & detailed	Analysis	Go/No Go

			design		
15	Yes	Performance requirements	Physical architecture & detailed design	Test	Unknown
16	Yes	Behavioural specification	Physical architecture & detailed design	Test	Risk reduction
17	Yes	General specification	Physical architecture & detailed design	Test	Unknown
18	No	System requirements	Final V&V	Test	High
19	No	Behavioural specification	Final V&V	Test	High
20	No	Behavioural specification	Final V&V	Test	High
21	No	Verification plan	Final V&V	Review	High

Table 3. Verification throughout the SE process has done by 1st workshop participants

6.2 Industrial feedback on the state of the art

In this section, the verification techniques classified from the state of the art (Table 2) are analysed against this industrial outlook. This involves analysing the effects of model-based verification in literature and current practice on the identified success criteria. None of the identified criteria were found to be directly measurable by the data collected; however, the influences of model-based verification were more tangible on certain criteria than others. This analysis focuses on these criteria. The results of this analysis for each technique are given in Table 4. C1 to C7 have been considered tangible because they are direct attributes of a model-based verification technique being utilized in an MBSE framework for a given project. The other three criteria C8 Reduction of verification overlaps, C9 Mastering of modelling efforts, and C10 Mastering of verification of complex systems would require for their evaluation measurable data collected between multiple projects in the same organization; which was not captured in this research.
Participants in the second workshop and interviewees have detailed their feedback on the state of the art. Their observations have been organized following the SE process phases detailed in the following sections.

6.2.1 Business or mission analysis and Stakeholder needs and requirements definition phase

Verification techniques V-BA.1 and V-Stk.1 are similar in nature as they both involve the review of diagrams representing the problem space, the stakeholders and their needs. In technique V-Stk.1, (Waite & Logan, 2011) suggest that the diagrams may be used to collaborate with the stakeholders. The stakeholders may "walkthrough" through the diagram and verify that the diagram represents all their needs. This method was widely used in different forms throughout the group with over 75% of participants saying that model-based methods improved the needs and stakeholder definition process. Additionally, the model-based techniques in this area may complement non-model-based ones such as Voice of Customer (VOC) and Quality Function Deployment (QFD). Organization 16 has shown success in utilizing this technique with SysML use case and behavioural diagrams for the development of novel surgical equipment. Additional value is added by reusing these artefacts in the System requirements and definition process for the definition of functional system requirements.

In relation to the 7 criteria, these methods provide a very early verification of the stakeholder specification by analysing it for completeness and coherency. By modelling the needs at a high abstract level, collaboration is enabled between different perspectives including the future users of the system. While the practice of diagramming is not new, the second workshop indicated that this data was being captured in the system model enabling it to be linked to other elements making up the system. The benefit of this practice was seen in Organization 12, as it allows them to clearly define the use case and scenarios under which the system shall be tested in final verification.

6.2.2 System requirements definition Phase

The literature review identified three verification practices prevalent in the Systems requirements definition process. The first V-SR.1 is to analyse the traceability of requirements to find errors in the specification and the other two are the execution of a black box model to verify the requirement specification through either formal or non-formal methods.

In V-SR.1, the authors (Kass & Kolozs, 2016) suggest the inclusion of originating needs in the system model to develop traceability between defined requirements and the total set of needs considered during the conception of the system. Analysis of the traces may take the form of a matrix where the absence or presence of traces between system requirements and originating needs may be easily verified. These traces allow for collaboration to identify which needs have been included and which have been left out and agreeance on the rational for choosing and dismissing certain needs. The survey conducted during the second AFIS workshop showed that the practice of importing originating needs as necessary for technique V-SR.1 was performed by two thirds of participants. This technique is seen to be useful for verifying the specification of requirements and aid in managing complex systems with many requirements. Additional-

ly, MBSE methodologies support the practice of reusing modelled requirements, meaning for this technique requirements may be imported from a pre-existing library or project (Smith, 2014). However, these two criteria stress the importance of requirement management, where a system model, and in particular the SysML language, have been seen to be weak (Caron, 2012) (Favaro et al., 2012). Researchers support the use of a requirement management tool which ideally may export or synchronize to the system model.

V-SR.2 and V-SR.3 involve the verification of a black box representation of a requirement specification. An example is shown by (Seidner et al., 2010) where the system model is verified by a formal model checking tool. The exchange between tools has shown success for the verification of the specification of functional, temporal, and external interface requirements. The method can be extended to focus on safety requirements by ensuring unsafe functions and states do not occur based on varied inputs. Techniques V-SR.2 and V-SR.3, black box modelling, were present with results of the second AFIS meeting showing that this technique has potential to be useful. Indeed, 70% of participants believe black box testing could be effective for verification. Data collected illustrated the use of formal methods as a method to verify specifications. Organization 14 applies such verification on mathematical models of the stakeholder and system requirements to iteratively update and find errors in the two sets of requirements. The difficulty experienced in this application is not necessarily the formal model checking but the formalization of requirements for use in the analysis. The text-based requirements must be interpreted correctly by the person building the model and retranslated correctly back into text after the test. Additionally, it has been found that practical application of formal methods requires breaking the black box representation to show some internal functions, effectively crossing abstract levels. However, the formal verification is useful for verifying safety and reliability requirements before moving into more detailed phases. Organization 6 uses black box testing for specifying subsystem elements whom exhibit complex behaviour. The understanding of this behaviour is later useful when specifying the surrounding subsystems. The tests may be reused progressively through the design process, to ensure that changes do not affect the target behaviour.

The collected data supports the literature that black box testing is a valid method for verification of a black box specification. While in most cases the interest is not on simulating an entire system level black box, the technique could be useful for isolating elements for verification such as critical requirements or subsystems with complex behaviour. These techniques verify the specification early, before the detail design of the internal functions of the system. In this way, they serve to early identify requirements in the specification whom are incoherent or infeasible. The ability to exchange information between the system model and specialized verification tools is also to be useful for the verification of critical safety and reliability requirements. However, the formalization of requirements in order to verify models is a key challenge as several researchers have identified that the formalization of requirements is not well accepted in many systems engineering communities (Schamai et al., 2016), that has been confirm by the interviewed panel. Despite this observation, one advantage of this formalization is that, once formalized, requirements become independent of their design, parameterizable, and reusable if a method can re-implement them in a new project.

An additional benefit of modelling the requirement specification was discovered in several organizations. Once created, the models act as information source for the behaviour of the system. Knowing the correct behaviour at a black level enables tests to be created as the engineer knows the correct response of the system per its use case, environment, and inputs. Organization 12 has found this information useful to include the behaviour directly in the test cases which occur in the final functional verification of the system. Another potential benefit comes from the fact that black box modelling imitates how many electrical products are bench-tested during the final verification stages. In these tests the system is connected to a simulated environment while test cases are executed and the behaviour of the system is monitored for requirement violations. While model-based testing has the potential to automatically produce every test case along with random cases for robustness testing, test cases representing failure modes of the system may be omitted as the correct system performance during dysfunctional behaviour is not specified. Researchers suggest model-based black box testing enables dysfunctional testing to be studied in the model and later compared to the behaviour of systems during final verification, a possible method to increase the completeness of verification.

6.2.3 Architecture definition phase

The various architectures views created during the Architecture definition process provide opportunities to verify the structures, behaviour, and requirements specified during this process. In the functional and logical architectures, functions and behavioural specification may be verified while in the physical, basic performance requirements may be tested. In both cases, verification using multiphysics simulation or by solving systems of differential equations is left for the Design definition process.

6.2.3.1 Functional and logical architectures

The quality of the functional and logical architectures may be verified in three ways without execution. Model-based review may provide metrics which suggest the correctness of an architecture (V-FA.1), traceability analysis may

show the requirement coverage to the decomposed and induced requirements (V-FA.2), and ontologies enable formal verification that construct rules are followed identifying errors in both design and modelling (V-FA.5).

The use of verification by architectural metrics (V-FA.1) was not prevalent in the participants of the second workshop. In one organization whom has used this technique it was found to be inefficient as engineers focused on designing to satisfy the metrics instead of requirements. On the other hand, the other two metrics were considered as key components to success in MBSE projects by the organizations with higher experience levels of MBSE. First traceability analysis (V-FA.2) is a key tool to ensure not only that decomposed and induced requirements are appropriately treated and linked to verification plans, but is an important method to access the impact of changes effecting the architecture either through changes in upstream requirements or constraints coming from the technological level. This impact analysis enables the other testing methods to be reused to verify only the portions of the architecture where it is necessary.

Secondly the use of construction rules (V-FA.5) was seen as extremely important to organizations 6 and 14 in order to utilize verification techniques and reuse or import models. The construction rules may limit how diagrams are used in the model or what connections are allowed. They support the implication of such rules in a meta-model and prefer SysML authoring tools which provide internal scripts to verify a system model against a meta-model. Going one step further these two organizations support the use of ontologies to verify construction rules developed by their organization. For all models to adapt to changes, import subsystems, and accept collaboration from multiple parties, the system model must remain coherent and useable. This offsets the freedom provided by semi-formal modelling languages, such as SysML, which does not guarantee proper integration between models made by different engineers. Organization 13 describes this as a key motivation for creating modelling rules applied across the entire development team. Having a correct architecture enables its reuse in future projects but also the ability to detect problems after changes and better trace requirements to their verification plans.

80% of participants in the second AFIS workshop believe that execution of functional architecture could be useful for early verification. In companies with higher experience levels, execution of architecture diagrams was focused on testing complex portions of the specification that were too difficult to manage without computer tools. These problem portions may be verified many times over the course of the project to ensure the architecture remains correct despite evolutions or changes to structure or behaviour. However, half of the organizations interviewed after the workshop cited that their current methods for verification were not sufficient. In some cases, they were unable to construct or maintain architectures or they were unable to decide between multiple candidate architectures. In many cases, they were unsure which if any aspects of the architecture would be valuable to verify, further validating the data collected in workshop 1 (see Table 3) suggesting that not all model-based verification is easily adaptable to the technical baselines in managing projects and verification results.

6.2.3.2 Physical architecture

Two techniques were presented in the state of the art to verify the specification of the physical architecture.

V-PA.1 is utilized to analyse the traceability as is performed in the logical architecture and V-PA.2 is the verification of the specification related to performance analysis with parametric diagrams. In the AFIS community the use of V-PA.1 mirrored that of V-FA.1 to verify the traces of induced and decomposed requirements and assess their impact in the case of changes. However, few examples of the use of parametric diagrams were seen in the second workshop. The parametric diagrams may be used to calculate equations whose value properties have been stored across the system model. In literature, the techniques were used to verify a performance requirement whose dependent values were scattered across the specification. Examples in AFIS of the use of parametric diagrams was only seen in conjunction with discipline modelling tools.

6.2.4 Design definition phase

The literature review presents four model-based verification techniques for the Design definition process with communication between the semantic system model and the domain tools being key to their use. However, in the second workshop few industrial examples of exploiting this data exchange were discovered either during the workshop or in the interviews afterwards, despite the presence of these discipline tools in many of the organizations as illustrated in Table 3. Additionally, participants were unconfident in the ability of the system model, specifically the physical architecture view, to act as a collaboration tool across disciplines with roughly only 20% of participants in the second workshop saying it would be very effective as a communication tool. This gap between practice and the state of the art highlights a possible lack of reuse of information stored in the system model for use to verify the domain models during detail design.

6.3 Second workshop outlines

The industrial data validated a number of the classified state of the art techniques. Starting with the techniques for stakeholder model collaboration, V-BA.1 and V-Stk.2. Both the literature and data sources show these techniques effec-

tive for stakeholder needs elicitation and analysis and as semantic diagrams are easily saved in the system model, they are reusable. However, the AFIS panel found that it was not always certain that their use for collaboration between stakeholders was efficient as there is no guarantee that two different parties understand a semantic model in the same manner. The system modeler must be careful to present something understandable to the target stakeholder without expressing a solution to their problem. This may take the form of transferring to a specialized modelling language in a certain industry standard or using a more adapted language for a large audience.

The use of verification techniques related to establishing traceability in the system model at all levels (V-SR.1, V-FA.2, and V-PA.1) were mirrored between the state of the art and industrial practices. In both sources, these techniques were viewed as methods to deal with complexity between modelling and abstraction levels and detect possible errors within the requirement specification when design changes occur. Techniques V-FA.2 and V-PA.1 may occur automatically; while V-SR.1 relates to stakeholder needs and is therefore based on human reasoning to determine if the appropriate needs have been included in the project. In the case of reused architectures and requirements, certain methodologies have suggested how packages including links between elements to perform traceability analysis may be reused to reduce the work of re-establishing traceability in each new project (Smith, 2014).

Additionally, black box testing was employed similarly between the two communities both in formal and informal versions. While its usage was not prolific within AFIS, the techniques V-SR.2 and V-SR.3 were considered useful to conduct early verification of specifications. In the case of AFIS, the focus of verification was in areas related to critical requirements before moving forward with the design. Additionally, examples were found of modeled black box specifications being reused to inform the system model design and later to build the final verification test cases. However, V-SR.3 formal model checking was seen to have a negative impact on C5 as the behaviour of a black box is difficult to predict accurately without specifying internal behaviour.

Generally, for the techniques related to testing architectures (V-FA.1 and V-FA.3), it was observed that the difficulty of modelling and maintaining exhaustive architectures along with a lack of know-how concerning effective testing dissuaded companies from investing in this type of verification. V-FA.1 was even seen to have a negative effect on C7, as one company with experience deploying quality metrics for system architecture did not find a positive influence on verification. However, a strong agreeance may be seen in V-FA.5, the use of ontologies to enforce architecture construction rules. As a formal method, ontologies do not need specific test cases for each requirement or between projects. Therefore, they may be reused and verification may occur automatically as the model is constructed. One strongpoint of using such ontologies is that they ensure the correct modelling rules are followed; allowing models to be imported, exported, or integrated between projects or into later stages of the current one. In this way, ontologies are expected to support certain criteria such as reusability and Organization 14 and 6 are implementing them in their practices.

For the verification techniques concerning the use of discipline models, virtual verification experience was widely seen at the industries studied. However, in these cases, communication between the system model and discipline simulation tools was not seen. Meaning that these verification steps were taken independently of the MBSE approach and therefore do not affect the success criteria.

7 DISCUSSION

In general, verification techniques were found to be the most frequently applied at high abstraction levels. High abstraction levels require less investment in terms of modelling while offering better understanding of use cases. Communication of these models was seen to impact all stakeholders. This included verification engineers, who were able to use the models to prepare their bench testing procedures.

The interviewed companies generally welcomed verification techniques for functional and logical architectures, but their capability to perform them remains below those seen in the literature. The cost of building and maintaining the model seems to have discouraged work in this direction.

Finally, while verification by simulation of discipline models was widely seen as very important for the interviewed companies, there was no evidence that an MBSE approach has a direct positive impact on these practices. This could be for two reasons. One, the literature identifies data transfer from the central system model (see (Friedenthal et al. 2014)) to the discipline models to be crucial to improving the efficiency of virtual verification. However, companies beginning to deploy MBSE have not had time to homogenize their toolchains and facilitate this transfer. This is corroborated by the study by Huldt and Stenius (2018) that showed that MBSE tools are available but not sufficiently tailored to organization's needs. Secondly, as described in the preceding paragraphs, modelling techniques at functional and logical architecture levels are not mature. So these primary modelling efforts are not reused at the discipline level decreasing positive impact and benefit/cost balance.

This first challenge of connecting a tool chain is mirrored in the state of the art literature. It can be viewed as a long-term goal for companies, researchers and tool vendors to increase the use of virtual verification in MBSE in the near future.

The second challenge of improving modelling at the functional and logical architecture levels is crucial for companies. The literature reviewed suggests that verification techniques at this architectural level have a positive impact on the identified success criteria. But it remains to be studied if increasing modelling investment has a positive impact on system development project. This doubt is strong in the community as shown in Huldt and Stenius (2018), that found the "lack of perceived value of MBSE" to be the second highest inhibitor in MBSE deployment, just after "cultural and general" habits.

Important barriers for engineers are: the perceived cost of MBSE approaches, the doubt in deciding the relevant modelling depth and the difficulties to connect architectural verification and component/discipline-specific verification. It is straightforward that work is still to be done to succeed in the generalization of a MBSE approach for V&V activities. The elicited criteria of Section 5 may be seen as an efficient guideline to MBSE tools developers, and also as elements to draw a consultancy strategy to accompany companies in their transition to MBSE.

The success criteria elicited from the industrial panel are relevant to sketch research directions. These criteria show the expectation of industrial user for model based V&V methodology. The adoption of such practices depends on the availability of efficient tools and relevant analysis methods, but also on appropriate organizational management strategies to accompany changes in the working standards. For methodologies on MBSE adoption, the reader may refer to proposals as the D3 MBSE adoption toolbox (Chami et al 2018). New V&V tools and methodologies will be adopted only if the expected performances are met. The criteria of section 5 clarify these expectations. The criteria are showing efficacy and efficiency needs. Table 5 gives the classification of criteria along these 2 aspects and formulates associated research direction to address them.

Efficacy	**Example of Research direction**	**Efficiency**	**Example of Research direction**
C5. Coherence between abstraction levels	*Enhancing expressiveness of SE languages*	*C1. Reuse of models*	*Model library management in tools. Versioning and import mechanisms*
C6. Detection & anticipation of problems	*New models for early V&V (on requirements, specification, functional architecture).*	*C2. Completeness of verification*	*New scalable V&V processes*
C7. Verification of specification	*New models for formal verification of requirements*	*C3. Test automation*	*Tool for test description generation; Test variants generator …*
C10. Mastering verification of complex systems	*New models & modelling artefacts for model follow up, V&V activities traceability…*	*C4. Collaboration and exchange tool*	*Work on model transformation, common encoding principles, co-simulation layers …*
		C8. Reduction of verification overlaps	*New model management processes. Better cross tool model exchange*
		C9. Master modelling efforts	*V&V strategy design including model management (granularity, reuse, expected precision…)*

Table 5. Classification of success criteria and research directions

To address efficacy needs, research works are to be done on defining new SE and V&V concepts. Theoretical contributions are needed on new modeling paradigms, languages and on analysis methods. As example, of this trend we may refer to works on designing formal methods (Chapurlat, 2013) for specification modeling (C7), and on introducing languages supporting coherence between abstraction levels (C5). The request for proposal (RFP) concerning the creation of SysML 2.0 (OMG, 2017) reveals the same idea as the efficacy need C10 as it insists on the need for new modeling concepts to trace and exhibit V&V activities in systems' models. The RFP states "SysML v2 [Shall] also support modeling concepts related to verification, analysis, and other concepts beyond what is in SysML v1".

The second research field highlighted by the criteria are on improving the tools and engineering processes. More efficiency is requested in many tools for models manipulation and exchange. Research direction to tackle those points are on model format, model transformation but also on defining relevant business cases to motivate tool providers in more efficient collaboration between their tools. The Functional Mockup interface standard definition (Blochwitz et al. 2011) illustrates this research direction. This project is dedicated to design the computer science technologies to enable co-simulation of models on different simulation software. Additionally to tools enhancement, research have to be done on engineering processes and modeling activities management. Mastering the modeling effort is of prime importance and methods are needed to define the right level of granularity to use. V&V process must also be rethink to define engineer-

ing policies capable of defining the right level of verification all along the projects. This is defining the right system part or behavior to be verified with the right level of details with the right confidence and the right resources. Good practices opportunities may be found in the lean design literature that could be a relevant complement to the V&V practices.

Before concluding, study limitation can be presented despite a rigorous approach was used as presented in section 2. Without minoring its value, as every qualitative survey, this study have to deal with potential quality issues and biases that have to be mentioned. Firstly, the set of participants is shaped by geographical and interests constraints. The workshop and meeting points for interviews were all in Rhône-Alpes region of France. Nevertheless, compared to most of industrial surveys in SE field that mainly examine defense & aerospace practices, this survey succeeds in gathering a heterogeneous panel of application domain. A second bias on the respondent set, is that participants were volunteers to attend the organized workshops, letting think that they are interested in SE advanced practices and on progressing in their V&V processes. It can be assumed that most of them are at least neutral or favorable to MBSE practices for V&V.

A researcher bias may be mentioned since our research team as a positive attitude toward MBSE practices. The company leading the study with our lab has also an important weight in the analyzed panel but it has been carefully balanced by interviews in complementary companies. Moreover the success criteria of section 5 have been obtained by consensus with participants of workshop 1 and are not representative of sole researcher point of view.

As stated in (Fanmuy & Foughali, 2012), engineering practices are very dissimilar between and within companies on topics related to SE. The V&V processes are very diverse, that makes possible universal conclusions irrelevant. A complementary bias that may be encountered in this kind of study is the absence of a common engineering language between engineers and organizations. These dissimilar understanding of MBSE terms has been shown in (Albers & Zingel, 2013). Despite clarification presentation and discussion were held during workshops, aligning all participants' understanding of SE terms remains difficult. The study should then be extended by defining profiles for sector or typology of enterprise as it is proposed for requirements management practice analysis in (Fanmuy & Foughali, 2012).

8 CONCLUSION

The paper present a survey of industrial practices on the use of Model-Based techniques for verification. Workshops and interviews were completed with 16 engineering organizations located in the Rhone-Alpes region of France. Firstly, key success criteria for integrating model-based verification with MBSE were identified. They gather companies' expectation for a successful adoption of Model-Based techniques for verification. To question the use of model-based techniques, an analysis of the promising model-based verification techniques found in literature was conducted with the panel to identify their feasibility and the barriers to their application.
The results of this industrial survey, highlighted in section 6.2, shows expressive lessons learnt and return of experience on the various Model-based verification techniques identified in the literature.

The findings of this study paint a picture of the current practices in integrating verification and MBSE and explore the impact of implementing such practices in companies beginning to adopt MBSE approaches. Agreement was discovered between many industrial and state of the art techniques conducted in the first processes of SE to verify stakeholder and system requirements; with many techniques relating to functional and behavioural requirements leading to more consistent verification during design and in the final verification stages.

At the same time, in both the state of the art and industrial practices, barriers were discovered about implementing techniques that meets the identified success criteria. It mainly concerns techniques for verifying architectures and detailed design. Namely, tit has been felt that the techniques for verifying architecture fail in supporting engineers on how to construct verifiable architecture.

Additionally, techniques related to the verification of multiphysics and discipline designs, important for error reduction in integration, were not seen to be efficiently integrated in current MBSE framework. Tool communication technical challenges and to lack of overall verification process within projects have been pointed as possible causes.

While these conclusion show that techniques in the above two areas remain difficult to deploy, the industrial perspectives collected in this research suggest that applying them could lead to a high positive impact on projects. Future research should focus on developing the verification techniques shown to impact the success criteria identified in this study. Several research directions have finally been proposed as a conclusion of the survey results discussion.

ACKNOWLEDGMENTS

The authors give thanks to all the workshop participants and the CRRA chapter of AFIS for supporting this research.

REFERENCES

Albers, A., & Zingel, C. (2013). Challenges of model-based systems engineering: A study towards unified term understanding and the state of usage of SysML. *Smart Product Engineering, 83-92*.

Andersson, C., & Runeson, P. (2002). Verification and validation in industry - A qualitative survey on the state of practice. *ISESE 2002 - Proceedings, 2002 International Symposium on Empirical Software Engineering*, 37–47.

Bajaj, M., Zwemer, D., Peak, R., Phung, A., Scott, A., & Wilson, M. (2011). 4.3. 1 Satellites to Supply Chains, Energy to Finance—SLIM for Model-Based Systems Engineering. *INCOSE International Symposium*, *21*, 368–394.

Baker, L., Clemente, P., Cohen, B., Permenter, L., Purves, B., & Salmon, P., 1996. Model Driven System Design Working Group: foundational concepts for model driven system design. *INCOSE International Symposium, 6(1), 1179–1185*.

Bjorkman, E. A., Sarkani, S., & Mazzuchi, T. A. (2013). Using model-based systems engineering as a framework for improving test and evaluation activities. *Systems Engineering*, *16*(3), 346–362.

Blessing, L. T., & Chakrabarti, A., 2009. DRM, a design research methodology. *Springer Science & Business Media*.

Blochwitz, T., Otter, M., Arnold, M., Bausch, C., Elmqvist, H., Junghanns, A., ... & Olsson, H. (2011, June). The functional mockup interface for tool independent exchange of simulation models. *8th International Modelica Conference; March 20th-22nd; Technical Univeristy; Dresden; Germany*, 105-114.

Böhm, W., Junker, M., Vogelsang, A., Teufl, S., Pinger, R., & Rahn, K. (2014, June). A formal systems engineering approach in practice: An experience report. In *Proceedings of the 1st International Workshop on Software Engineering Research and Industrial Practices*, 34-41

Bransden, T., Do, Q., Farrell, D., & Taylor, S. (2017). The application of mbse to inform workforce decision making. *Incose International Symposium.* 27,(1), 386-400.

Caron, F. (2012). 6.5. 1 A collaborative process based on systems engineering and mechatronics methods. INCOSE International Symposium, 22, 829–849.

Carson, R. S., & Kohl, P. V. (2013). 9.5.2 New Opportunities for Architecture Measurement. INCOSE International Symposium, 23(1), 271–276

Chami, M., Aleksandraviciene, A., Morkevicius, A., & Bruel, J. M. (2018, July). Towards solving MBSE adoption challenges: the D3 MBSE adoption toolbox. *INCOSE International Symposium.* 28 (1), 1463-1477.

Chapurlat, V. (2013). UPSL-SE: A model verification framework for Systems Engineering. *Computers in Industry*, 64(5), 581-597.

Crisp, H. E. 2007. Systems engineering vision 2020. Seattle, Washington

Do, Q., Cook, S., & Lay, M. (2014). An investigation of MBSE practices across the contractual boundary. *Procedia Computer Science*, *28*, 692-701.

Douglass, B. P. 2015. Agile systems engineering. *Morgan Kaufmann.*

Engström, E., & Runeson, P. (2010). A qualitative survey of regression testing practices. *Procedings of 11th international Conference PROFESS 2010*, 3–16.

Fanmuy, G., & Foughali, G. (2012). A survey on Industrial Practices in Requirements Engineering. *INCOSE International Symposium*. 22(1). 1021-1040.

Favaro, J., Mazzini, S., Schreiner, R., de Koning, H.-P., & Olive, X. (2012). 3.6.2 Next Generation Requirements Engineering. *INCOSE International Symposium*, *22*(1), 461–474.

Frank, M., Broodney, H., Orion, U., & Kordova, S. K. 2016. From Common Strategies and Approaches to Virtual Integration. *In INCOSE International Symposium, 26, 1988-1999.*

Friedenthal, S., Moore, A., & Steiner, R. (2014). *A Practical Guide to SysML: The Systems Modelling Language*. Morgan Kaufmann.

Gopinathan, H., Tocci, A., Ciambra, F., & Frisoni, D. (2012). 3.6.1 Rapid prototyping and validation of Human factors model in a Model Based Naval Systems Engineering Application. INCOSE International Symposium, 22(1), 448–460.

Gough, K. M., & Phojanamongkolkij, N. (2018). Employing Model-Based Systems Engineering (MBSE) on a NASA Aeronautic Research Project: A Case Study. In *2018 Aviation Technology, Integration, and Operations Conference*

Huldt, T., & Stenius, I. (2018) State-of-practice survey of model-based systems engineering. *Systems Engineering*, 1-12.

INCOSE, 2015. Systems engineering handbook: A guide for system life cycle processes and activities. *Ed. Walden, D. D., Roedler, G. J., Forsberg, K., Hamelin, R. D., & Shortell, T. M. – Wiley*

Kass, N., & Kolozs, J. (2016). Getting Started with MBSE in Product Development. *INCOSE International Symposium*, *26*(1), 526–541

Laing, C., 2017. Towards the integration of verification in Model-Based Systems Engineering. *Master thesis dissertation Grenoble-INP.*

Le Dain, M.-A., Blanco, E., & Summers, J. D. (2013). Assessing design research quality: investigating verification and validation criteria. *ICED13 International Conference on Engineering Design*.

Maropoulos, P. G., & Ceglarek, D. 2010. Design verification and validation in product lifecycle. *CIRP Annals - Manufacturing Technology*, *59*(2), 740–759.

Murphy, L., & Collopy, P. 2012. A work-centered perspective on research needs for systems engineering with models. *Procedia Computer Science*, *8*, 315–320.

NDIA, 2011. Final Report of the Model Based Engineering Subcommittee of the National Defense Industrial Association (NDIA).

Neill, C. J., & Laplante, P. A. (2003). Requirements Engineering: The State of the Practice Revisited. *IEEE Software*, 40–45.

OMG Object Management Group (2017) Systems Modeling Language (SysML®) v2 Request For Proposal (RFP). December, 2017.

Pétin, J.-F., Evrot, D., Morel, G., & Lamy, P. (2010). Combining SysML and formal methods for safety requirements verification. *22nd International Conference on Software & Systems Engineering and Their Applications*.

Quintana, V., Rivest, L., Pellerin, R., Venne, F., & Kheddouci, F. 2010. Will Model-based Definition replace engineering drawings throughout the product lifecycle? A global perspective from aerospace industry. *Computers in Industry, 61(5)*, 497-508.

Robson, C., & McCartan, K. (2016). *Real world research* (Fourth Edi). Wiley

Runeson, P., Andersson, C., & Höst, M. (2003). Test processes in software product evolution - A qualitative survey on the state of practice. *Journal of Software Maintenance and Evolution*, *15*(1), 41–59.

Rungtusanatham, M. J., Choi, T. Y., Hollingworth, D. G., Wu, Z., & Forza, C. (2003). Survey research in operations management: historical analyses. *Journal of Operations Management*, *21*(4), 475–488

Schamai, W., 2013. Model-Based Verification of Dynamic System Behaviour against Requirements : Method, Language, and Tool. *Doctoral dissertation, Linköping University*

Schamai, W., Helle, P., Albarello, N., Buffoni, L., & Fritzson, P. (2016). Towards the Automation of Model-Based Design Verification. *INCOSE International Symposium*, *26*(1), 585–599.

Seidner, C., Lerat, J.-P., & Roux, O. H. (2010). Simulation and Verification of [Dys] functional Behaviour Models: Model Checking for SE. In *INCOSE International Symposium*. 20, 681–693.

Smith, W. B., 2014. Re-Use Libraries Leveraging Model-Based Systems Engineering to greatly increase engineering productivity. *INCOSE International Symposium*, *24*(1), 298–312.

Shokry, H., & Hinchey, M. (2009). Model-Based Verification of Embedded Software. *IEEE Computer*, *42*(4), 53–59.

Vogelsang A., Amorim T., Pudlitz F., Gersing P., & Philipps J. (2017). Should I Stay or Should I Go? On Forces that Drive and Prevent MBSE Adoption in the Embedded Systems Industry. *Product-Focused Software Process Improvement. PROFES 2017. Lecture Notes in Computer Science*, 10611.

Waite, M., & Logan, P. (2011). Model based user needs analysis. In *Systems Engineering and Test and Evaluation Conference (SETE2011), Canberra* 7.

Wagner, D. A., Bennett, M. B., Karban, R., Rouquette, N., Jenkins, S., & Ingham, M. (2012). An ontology for State Analysis: Formalizing the mapping to SysML. In *Aerospace Conference, 2012 IEEE.* 1–16.

Weidenhaupt, K., Pohl, K., Jarke, M., & Haumer, P. (1998). Scenarios in System Development. *IEEE Software*, 34–45.

White, C. J., & Mesmer, B. L. (2019). Research needs in systems engineering: Report from a University of Alabama in Huntsville workshop. *Systems Engineering*, (March), 1–11.

+ Positive impact
- Negative impact
+/- Barriers exist to obtain a positive impact
"blank cell" : Unknown impact
SOTA : identified in state of the art

				C1		C2		C3		C4		C5		C6		C7	
				Reuse of models		Completeness of verification		Test automation		Collaboration and exchange		Coherence between abstraction levels		Detection and anticipation of problems		Verification of specification	
				SOTA	AFIS	SOTA	AFIS	SOTA	AFIS	SOTA	AFIS	SOTA	AFIS	SOTA	AFIS	SOTA	AFIS
V-BA.1	Semantic review	Semantic Diagrams	Completeness of problem space	+	+					+	+/-	+	+			+	+
V-Stk.1	Semantic review	Behavior diagram	Stakeholder and needs identification completeness	+	+					+	+/-	+	+			+	+
V-SR.1	Semantic review	Requirement diagram	Completeness of system requirements	+		+	+			+	+	+	+	+	+	+	+
V-SR.2	Testing	Executable form of semantic diagram(s)	System requirement specification		+	+	+					+		+	+	+	+
V-SR.3	Formal - Model Checking	Executable form of semantic diagram(s)	System requirement specification	+		+	+	+	+			+	-	+	+	+	+
V-FA.1	Semantic review	Semantic architecture	System architecture quality	+		+		+						+		+	-
V-FA.2	Semantic review	Requirement diagram	Requirement traceability	+		+	+	+	+	+	+	+	+	+	+	+	+
V-FA.3	Testing	Executable form of semantic diagram(s)	System requirements specification	+		+	+	+						+	+	+	+
V-FA.4	Formal - Model checking	Executable form of semantic diagram(s)	System requirement specification	+		+		+						+		+	
V-FA.5	Formal – Ontology	Semantic architecture	System architecture correctness	+	+	+	+	+	+		+			+	+	+	
V-PA.1	Semantic review	Requirement diagram	Requirement traceability	+		+	+	+	+	+	+	+	+	+	+	+	+
V-PA.2	Semantic review	Parametric diagram	Requirement specification	+		+		+						+		+	
V-DD.1	Test	Multiphysics system model	System requirement specification	+/-		+		+/-						+		+	
V-DD.2	Test	Multiphysic system model	System requirements	+/-		+		+/-						+			
V-DD.3	Review (3D model)	Discipline simulation model	System requirement specification	+/-		+		+/-						+		+	
V-DD.4	Test	Discipline simulation model	System requirements	+/-		+		+/-						+			

Table 4 Influence of techniques on success criteria

+Positive Impact - Negative impact +/- Barriers exist to obtain a posituve impact "Blank cell" : Unknown impact SOTA : identified in state of the art				C1		C2		C3		C4		C5		C6		C7	
				Reuse of models		Completeness of verification		Test automation		Collaboration and exchange		Coherence between abstraction levels		Detection and anticipation of problems		Verification of specification	
				SOTA	AFIS	SOTA	AFIS	SOTA	AFIS	SOTA	AFIS	SOTA	AFIS	SOTA	AFIS	SOTA	AFIS
V-BA.1	Semantic review	Semantic Diagrams	Completeness of problem space	+	+					+	+/-	+	+			+	+
V-Stk.1	Semantic review	Behavior diagram	Stakeholder and needs identification completeness	+	+					+	+/-	+	+			+	+
V-SR.1	Semantic review	Requirement diagram	Completeness of system requirements	+		+	+			+	+	+	+	+	+	+	+
V-SR.2	Testing	Executable form of semantic diagram(s)	System requirement specification		+	+	+					+		+	+	+	+
V-SR.3	Formal - Model Checking	Executable form of semantic diagram(s)	System requirement specification	+		+	+	+	+			+	-	+	+	+	+
V-FA.1	Semantic review	Semantic architecture	System architecture quality	+		+		+						+		+	-
V-FA.2	Semantic review	Requirement diagram	Requirement traceability	+		+	+	+	+	+	+	+	+	+	+	+	+
V-FA.3	Testing	Executable form of semantic diagram(s)	System requirements specification	+		+	+	+						+	+	+	+
V-FA.4	Formal - Model checking	Executable form of semantic diagram(s)	System requirement specification	+		+		+						+		+	
V-FA.5	Formal – Ontology	Semantic architecture	System architecture correctness	+	+	+	+	+	+		+			+	+	+	
V-PA.1	Semantic review	Requirement diagram	Requirement traceability	+		+	+	+	+	+	+	+	+	+	+	+	+
V-PA.2	Semantic review	Parametric diagram	Requirement specification	+		+		+						+		+	
V-DD.1	Test	Multiphysics system model	System requirement specification	+/-		+		+/-						+		+	
V-DD.2	Test	Multiphysic system model	System requirements	+/-		+		+/-						+			
V-DD.3	Review (3D model)	Discipline simulation model	System requirement specification	+/-		+		+/-						+		+	
V-DD.4	Test	Discipline simulation model	System requirements	+/-		+		+/-						+			