Functional Mock-up Interface: An empirical survey identifies research challenges and current barriers

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Abstract

Co-simulation is a promising approach for the analysis of complex, multi-domain systems, that leverages mature simulation tools of the respective domains. It has been applied in many different disciplines in academia and industry, with limited sharing of findings. With the increasing adoption of the FMI standard, researchers have set to work on surveying the scattered knowledge on co-simulation in academia. This paper complements the existing surveys by taking on the social and empirical aspect, corroborating, and prioritizing, previous findings. We focus on understanding the perceived research challenges, and the current barriers, based on expert assessment. One of the main barriers pointed out is the limited support for discrete event and hybrid co-simulation.

Keywords: Co-Simulation, Functional Mock-Up Interface, Modelling

1 Introduction

As engineered systems become more complex, whole system simulation techniques need to keep up with the increasing plethora of tools used in the development process. It is no longer reasonable to expect the existence of a one-size-fits-all modelling and simulation tool, capable of reproducing the behavior of a complex heterogeneous system, across the many development stages (Van der Auweraer et al., 2013; Vangheluwe et al., 2002). Instead, highly specialized modelling and simulation tools, each tailored to the needs of a specific engineering domain through years of research and development, should be integrated, to allow engineers to glimpse at the inter domain interactions of a coupled system.

For simulation, this integration can in theory be performed by describing how each of the models are translated to a uniform behavioral model, as suggested in (Vangheluwe, 2008). However, the existence of specialized suppliers with valuable Intellectual Property (IP), the subtleties of accurately simulating some formalisms, the sheer number of different modelling and simulation tools and accompanying licensing fees, make this approach, denoted as co-modelling, infeasible in practice.

A pragmatic solution, called co-simulation (Gomes et al., 2018b; Hafner and Popper, 2017), is to perform the model integration at the dynamic behavioral level, where each model is used to produce a black box that consumes inputs and produces outputs over time. These black boxes, each representing the behavior of a subsystem/domain, can then be interconnected to mimic the interconnections of the corresponding subsystems. These interconnections frequently form feedback loops, which means that the behavior of one black-boxes, up to a simulated time point t, is only specified when the behavior of all the other interacting black-box has been computed up to t. The consequence is that the behavior of each black box must be computed in lock-step with the other black boxes, through the aid of a master algorithm. The master algorithm is responsible for: finding the appropriate initial values for every black-box; coordinating the progression of the simulated time; obtaining outputs and feeding inputs from/to the black-boxes; and instructing each black box to compute the next set of outputs. The algorithm is oftentimes summarized in time diagrams such as the one shown in Figure 1.

Co-simulation yields multiple advantages:

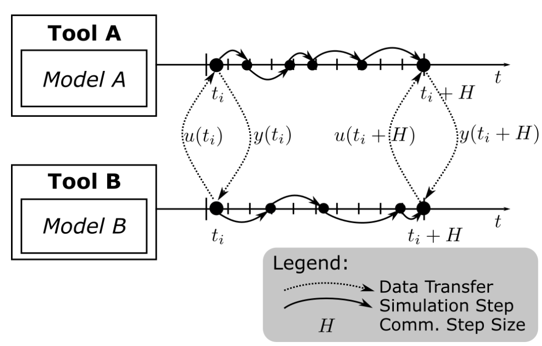

Figure 1. Example master algorithm.

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- The behavioral level seems to be the simplest level any subsystem integration can be done, and is common across all behavioral formalisms;
- Each black box incorporates its own simulation algorithm, usually the most adequate for its domain;
- The exchange of the black box models can be made without requiring their content to be disclosed, thereby protecting IP, and avoiding licensing fees.

Unfortunately, naively connecting inputs to outputs on black boxes does not necessarily imply that the resulting behavior mimics the actual couplings of the subsystems, which brings us a main research problem in co-simulation: *are the co-simulation results trustworthy?*

This is not a new challenge, and the coupling of simulators can be traced back to multi-rate simulation techniques. However, the increasing number of applications in different domains (Schweiger et al., 2018a), have led researchers to survey the vast and scattered body of knowledge in co-simulation. For example, (Hafner and Popper, 2017) discusses the differences in terminology used regarding co-simulation. They provide a classification of existing co-simulation methods, which highlights the unexplored methods. With the intent of systematically surveying the academic state of the art, (Gomes et al., 2018b) introduces the fundamental concepts, and applies feature oriented domain analysis to construct a taxonomy of functional and non-functional requirements of co-simulation. This highlights the multiple ways in which information about the black-boxes can be exposed to attain more reliable results. The work in (Palensky et al., 2017) introduces the main concepts in co-simulation in a tutorial fashion. Despite its focus on power systems, it covers the main methods thoroughly, highlighting the pros and cons of each, and providing pointers to more detailed expositions.

To the best of our knowledge, even though co-simulation has been used in industry, there is no empirical assessment of its use, nor of the challenges described in the above surveys. Only (Bertsch et al., 2014) reports on the industrial use of co-simulation, and highlights some of the practical challenges in such a setting, but from the authors' experiences. There have been many other applications of co-simulation even since this report was published.

In this paper, we complement the existing survey work by taking on the social and empirical aspect. We collected interviews with international experts from various fields (both academic and industry) regarding applications, barriers and future challenges of Functional Mock-up Interface (FMI). The results presented here are part of a larger survey effort on co-simulation, whose results are still being collected. The FMI (Blockwitz et al., 2012; FMI, 2014) is a standard that enables co-simulation by providing a common interface to couple black box simulators. We focus on FMI based co-simulation, because of its adoption in various fields in industry and academia (Brembeck et al., 2011; Schweiger et al., 2018a; Bünte et al., 2014; Engel et al., 2018; Sanfilippo et al., 2018; Schweiger et al., 2018b) as well as increasing citations among scientific papers (see Figure 2).

In the next section, we describe our methodology, and in the section after, we summarize the main results and conclusions.

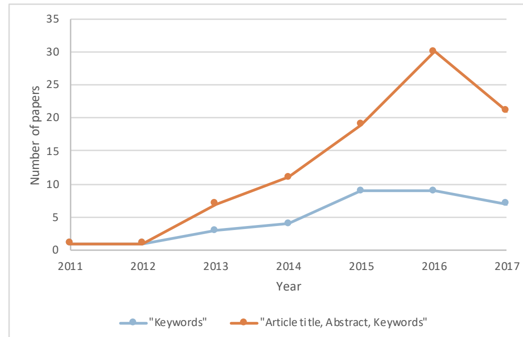

Figure 2. Example master algorithm.

2 Method

As a methodological foundation of this study, the Delphi method was adopted. The Delphi method is a forecasting technique with which the opinions from a defined group of experts are systematically collected and compiled (Hsu and Sandford, 2007). It enables the empirical investigation of research questions on topics that are characterized by an incomplete state of knowledge (Powell, 2003), a lack of historical data or a lack of agreement in the studied field (Okoli and Pawlowski, 2004). A Delphi study aims at achieving a reliable consensus of opinion, by conducting a repetitive assessment process that includes controlled opinion (Linstone and Turoff, 2002). As a formal consensus methodology, the Delphi method provides structured circumstances that "[...] can generate a closer approximation of the objective truth than would be achieved through conventional, less formal, and pooling of expert opinion" (Balasubramanian and Agarwal, 2012). We considered this method because it is especially useful for addressing interdisciplinary research problems, where the experts' opinions are heterogeneous

Regarding the number of experts, Clayton (1997) indicated that 15-30 experts with homogeneous expertise background or five to ten experts with heterogeneous background should be involved in a Delphi process, while Adler and Ziglio (1996) argued that 10–15 experts with homogeneous expertise can already be considered appropriate.

The quality of the Delphi process depends on the factors of creativity, credibility and objectivity (Nowack et al., 2011) and to address these quality criteria we followed acknowledged guidelines by authors such as (Landeta, 2006; Nowack et al., 2011; Okoli and Pawlowski, 2004).

For the selection of the sample of participants, we used a Knowledge Resource Nomination Worksheet (KRNW) as a framework (Okoli and Pawlowski, 2004). The KRNW is a general criterion for sampling an expert panel to be included in a group technique study and consists in the following five steps (Delbecq et al., 1975): (1) Preparation of the KRNW; (2); Population of the KRNW; (3) Nomination of additional experts; (4) Ranking of experts; and (5) Invitation of experts (Okoli and Pawlowski, 2004).

In step 1, experts from academia and industry were selected, as we considered both perspectives essential. In step 2, the category academia was populated based on a keyword-based search in the relevant literature. The category of industry experts was compiled based on a keyword-based search in the relevant literature, the experience of the research group and consultation with practitioners. In step 3, both categories were expanded, based on the suggestions received after contacting the initial list of experts. The ranking of experts in step 4 was based on the number of publications (www.scopus.com). In step 5 the final list of 15 experts was invited to take part in the first phase of the Delphi study via an online-questionnaire.

The survey consist of two rounds. The choice of rounds is justified by, for instance, Sommerville, which argues that the changes in the participants' views in most cases occurred in the first two rounds of the study and not many new insights are gained on further rounds (Somerville, 2008). Table 1 summarizes the aim and approach of each round and provides the number of participants per category.

Table 1. Summary of the 2-stage Delphi process. Participants A=Academia, I=Industry, ND=not declared.

			Participants			
Round	Aim	Approach	A	I	ND	Total
1	Identification of research needs, SWOT factors, limitations and possible extensions of the FMI standard	Qualitative	7	2	3	12
2	Evaluation of the result from the first round and developing in-depth discussions on the key aspects.	Semi-quantitative	17	11	0	28

Relevant questions regarding FMI in the first round were selected based on existing literature studies (e.g. (Gomes et al., 2018b; Palensky et al., 2017; Trcka et al., 2007) and the experience of the authors. Both rounds included both open-ended (qualitative) and quantitative questions.

In the first round, the majority of questions was qualitative, whereas in the second, quantitative. This ensures that the topic is introduced in a general way in the first round. If the first round consisted only of quantitative questions, there would be an increased risk of overlooking important factors or biasing the results.

The qualitative questions in the first round concerned only with findings that were common across the survey papers referred above. In these cases, expert opinions were used to evaluate findings in previous surveys and to enable quantitative statements and comparisons (e.g. how important is the extension of the FMI standard in area "a" versus "b").

The quantitative questions in the second round were mainly formulated based on the results of the first round and the findings in recent literature (e.g. when contradictions were identified).

A total of 28 experts answered the FMI relevant questions presented in this paper. Experts from academia who took part in the survey, work in the following fields: Software development, Energy Systems, Mobility and Maritime. Experts from industry, who took part in the survey, work in the following sectors: Energy Systems, Software development, Mobility. Some experts did not provide information about their field or sector.

A seven-point Likert scale was used to measure the quantitative responses (Entirely agree =7 to Entirely disagree = 1). In order to provide a transparent presentation of the results, (i) in the appendix, all results are displayed in detail in a bar chart and (ii) in Section 3 we present a summary table including Mean, Median and Interpolated Median values (Balasubramanian and Agarwal, 2012; Hallowell and Gambatese, 2010; Sachs, 1997)). There is an ongoing discussion about the best way to interpret Likert scales; Sachs argues that the interpolated median is more precise than the normal medians because of better consideration of frequencies of answers within one category in comparison to all answers (Sachs, 1997).

3 Results and Discussion

Table 2 summarizes the results from the second round of quantitative questions; more details can be found Figure 3.

The questions focus on the issues reported by the experts in the first round of the survey, and on the exiting literature. Based on the score provided by the experts to each question, we classified each issue according whether it constitutes a barrier for the adoption of the standard: issues with a median score less than 4 are considered as "Not a barrier"; issues with a median score between 4 and 5 are considered as "Somewhat of a barrier"; and issues with a median score of 5 or higher are considered as a "Barrier".

For example, concerns with IP protection, with a median score of 3.0, do not constitute a barrier for the adoption of FMI. This corroborates the fact that one of the goals of FMI is to provide adequate IP protection (Blochwitz et al., 2011). This result does not necessarily contradict what is stated in (Durling et al., 2017), as that work concerns advanced use cases of co-simulation, such as design space exploration, or solving boundary conditions. As the authors suggest, it is likely that advanced co-simulation methods, or those providing formal guarantees (e.g., (Thule et al., 2018)), will require some information from the models.

We also tested the results on disagreement between experts from academia and industry using a Chi-square test. We found disagreement for the question: "There is a

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lack of (scientific) community, forums, groups" ($p<0.05$). Whereas the majority of industry experts did not consider it a barrier (median=3), experts from academia provided mixed answers (median=4).

In the following, we discuss the issues that experts consider to be barriers.

3.1 FMI has limited support for hybrid and discrete time co-simulation

Informally, a hybrid co-simulation is the co-simulation of a hybrid system (cf. (Gomes et al., 2017) for more details and examples). Hybrid systems exhibit a mix of continuous and discrete event dynamics; e.g., systems modelled with hybrid automata (Henzinger, 2000), switched systems (Sun, 2006), etc.

The ability to reproduce the dynamics of these systems in a co-simulation is important because, in full system evaluations, where co-simulation is frequently used (Van der Auweraer et al., 2013), hybrid dynamics are pervasive. For example, systems exhibiting Coulomb friction and/or hysteresis, or comprising non-trivial control software, all exhibit hybrid behavior.

In the FMI for co-simulation, version 2.0 (FMI, 2014), some support is provided to locate discontinuous events. However, according to the covered literature, providing support for hybrid co-simulation includes addressing the following challenges:

- Sound representation of different semantics (as done in (Ptolemaeus, 2014; Cremona et al., 2016) and semantic adaptations (Gomes et al., 2018a);
- Accurate event location (e.g., as done in (Zhang et al., 2008; Broman et al., 2013));
- Discontinuity identification and signal distinction (e.g., using the super-dense integer time formalization (Broman et al., 2015; Cremona et al., 2017a), or explicitly representing internal clocks (Franke et al., 2017); and
- Adequate discontinuity handling (e.g., set the internal continuous numerical solvers' state (Andersson et al., 2016)).

3.2 There is insufficient documentation

Detailed documentation, tutorials and examples are of central importance for the establishment of a technology such as co-simulation. Previous works have already addressed this barrier. (Palensky et al., 2017) presents a good introduction for researchers looking to understand the main co-simulation algoritms, and what their trade-offs are.

It is also important to mention that some tutorials have been published on individual standards or in the context of co-simulation projects. Within the the INTO-CPS (Larsen et al., 2016) project, for example, tutorials with industrial case studies were developed and training schools were organized. There are also tutorials for the FMI standard (FMI, 2018); some tool vendors also provide video tutorials on social media platforms such as Youtube.

The revision and/or introduction of online learning material based on insights into success factors in online education would be helpful (Volery and Lord, 2000; Sun et al., 2008). This should include real-world examples from different fields. Furthermore, the possibilities, problems and limitations of applications in the field of continuous, discrete event and hybrid co-simulation should be presented. In order to sustain a long term adoption of the standard and to lower the entry barrier for new user, it is important to manage expectations of what co-simulation can, and cannot, do. This includes e.g. licensing issues, computational performance in comparison to monolithic simulations. The integration of FMI into university courses would increase the visibility of the standard and accelerate the development of (online) learning materials and tutorials.

3.3 The standard does not support certain requirements that would be widely needed by industry and academia

The authors are aware that this statement is very general and answers based on Liker Scales do not allow general conclusions; several extensions to the standard have been proposed from tool vendors (e.g. (Sahlin and Lebedev, 2016)), industry (e.g. (Hirano et al., 2015) and academia (e.g. (Cremona et al., 2017b; Broman et al., 2013)). Some of these proposed extensions are addressed in the current development process (FMI, 2018). In addition to the ongoing FMI development process, we propose a comprehensive empirical study to clarify which extensions are needed by which actors in industry and academia. In this context, one expert pointed out that if all extensions and peculiarities of individual tools are considered, there is a risk that the robustness of applications will be reduced. Therefore, the proposed empirical study should also include theoretical experts, tool and members of the FMI development committee.

3.4 Lack of transparency in in features supported by FMI tools

Potential users usually have a clear idea of the modeling requirements when addressing a problem with co-simulation. Based on these requirements, a screening of possible alternatives often follows. A transparent and easy-to-understand presentation of supported features is of central importance in this context. We propose two actions: (i) which features are supported, and which are not, should also be addressed in online learning materials and tutorials (see section 3.2); and (ii) a transparent and frequently updated online presentation of supported features and planned extensions.

3.5 Limitations of the study

The aim of this study is to identify barriers to FMI by means of empirical surveys and to link and critically reflect on findings from recent literature. How these barriers could be overcome was also discussed in relation to re-

Table 2. Expert assessment of current barriers for FMI based on a Seven-point Likert scale.

Score: Entirely agree (7) Mostly agree (6) Somewhat agree (5) Neither agree nor disagree (4) Somewhat disagree (3) Mostly disagree (2) Entirely disagree (1)	Mean	Median	Interpolated Median
Not a Barrier			
It is difficult to post-process simulation results	3.57	2.50	**2.50**
Concerns of industry/academia regarding FMI and IP protection	3.52	3.00	**2.83**
No pre-implemented Master Algorithms	4.08	3.00	**3.25**
Somewhat of a Barrier			
The FMI-standard still requires a number of updates in order to serve as a useful general standard for co-simulation	4.52	4.00	**3.75**
There is not enough cooperation and exchange (theoretical/numerical, implementation, application/industry) in defining and developing the FMI standard	4.12	4.00	**3.81**
There is a lack of tools that sufficiently support FMI	4.04	4.00	**3.83**
There is a lack of (scientific) community, forums, groups	4.27	4.00	**3.83**
Simulations are slow compared to monolithic simulations	3.82	4.00	**3.92**
It is difficult to implement FMU's (API, connecting/linking different subsystems)	4.07	4.00	**4.00**
Barrier			
FMI has limited support for hybrid co-simulation and it is not easily applicable	5.82	5.00	**5.00**
Lack of transparency in features supported by FMI tools	5.12	5.00	**5.05**
There is insufficient documentation and a lack of examples, tutorials, etc.	5.14	5.00	**5.17**
The standard does not support certain requirements that would be widely needed by industry and academia	5.42	5.00	**5.25**
FMI has limited support for discrete co-simulation and it is not easily applicable	5.67	5.00	**5.25**

cent literature. The identification of new approaches and the quantitative and qualitative evaluation and comparison of existing approaches for the respective barriers is beyond the scope of this paper.

The barrier *"The standard does not support certain requirements that are urgently needed by industry and academia"* is very general and a detailed discussion goes beyond the scope of this paper. The authors admit that ideally, experts should have been asked in detail about these requirements. Nevertheless, we did not want to withhold these results, as they could stimulate a broader discussion on that topic.

A further limitation of the present study concerns the size of the sample. However, the aim of Delphi studies is not to obtain a representative sample in a purely statistical sense. The number of experts participating in this study is in line with recommendations from relevant literature on Delphi studies (Adler and Ziglio, 1996; Clayton, 1997; Ludwig, 1997). A general critical discussion about the Delphi method and its weaknesses can be found here (Goodman, 1987; Hill and Fowles, 1975).

4 Conclusion

The present paper reports an expert assessment on FMI, taking on the social and empirical aspect, with a focus on understanding the perceived research challenges and the current barriers. After a two-round Delphi-method, we concluded that experts consider the following as barriers to the adoption of the standard:

1. limited support for hybrid- and discrete event co-simulation;
2. insufficient documentation and a lack of examples and tutorials;
3. lack of certain requirements that would be widely needed by industry and research; and
4. transparent presentation of supported features;

It is our hope that the results of this study increase transparency and facilitate a structured development of the standard, and related research.

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6 Appendix

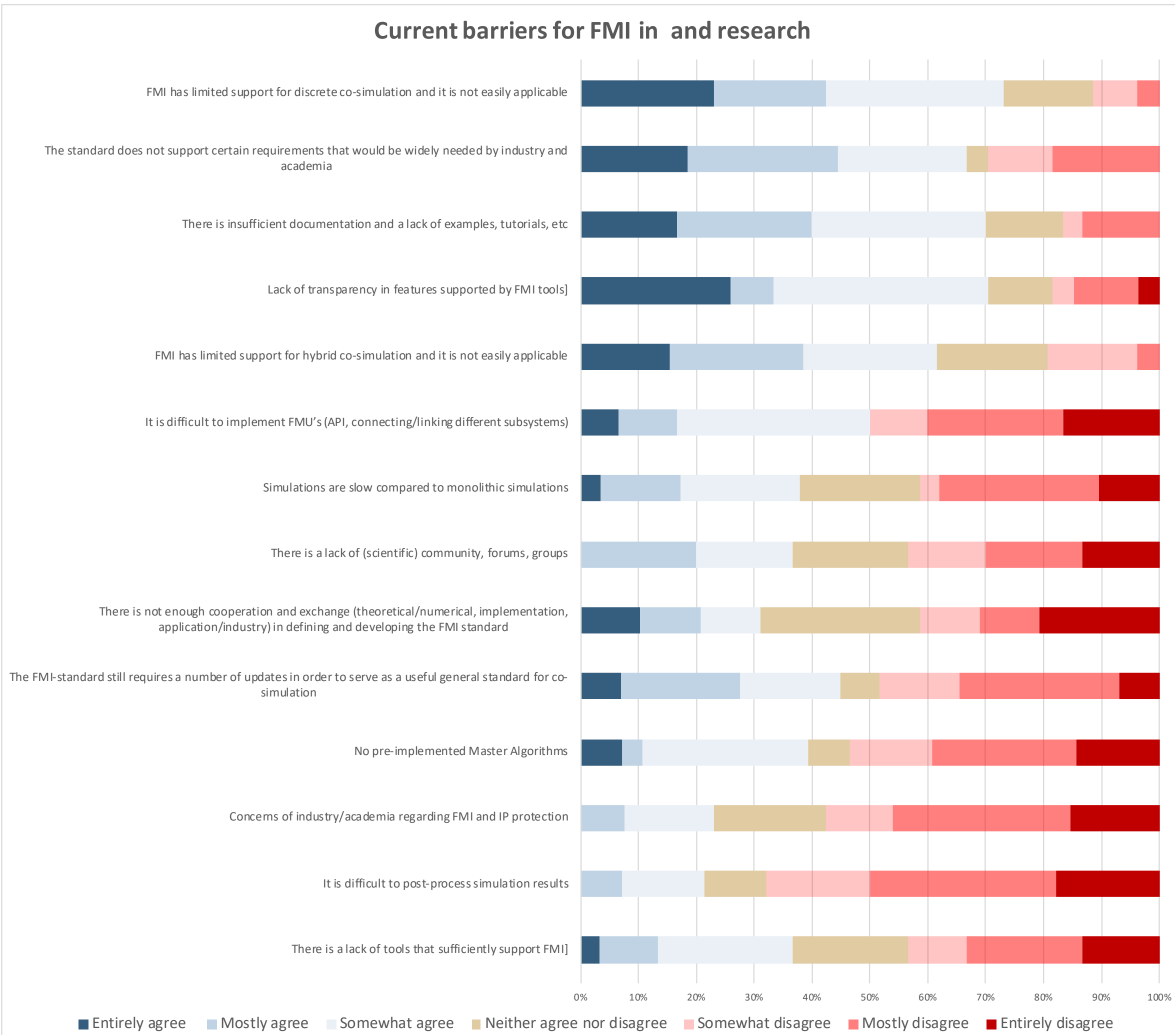

Figure 3. Expert assessment of current barriers for FMI based on a Seven-point Likert scale.

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