An Empirical Survey on Co-simulation: Promising Standards, Challenges and Research Needs

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Abstract

Co-simulation is a promising approach for the modelling and simulation of complex systems, that makes use of mature simulation tools in the respective domains. It has been applied in various different domains, oftentimes without a comprehensive study of the impact to the simulation results. As a consequence, over the recent years, researchers have set out to understand the essential challenges arising from the application of this technique. This paper complements the existing surveys in that the social and empirical aspects were addressed. More than 50 experts participated in a two-stage Delphi study to determine current challenges, research needs and promising standards and tools. Furthermore, an analysis of the strengths, weakness, opportunities and threats of co-simulation utilizing the analytic hierarchy process resulting in a SWOT-AHP analysis is presented. The empirical results of this study show that experts consider the FMI standard to be the most promising standard for continuous time, discrete event and hybrid co-simulation. The results of the SWOT-AHP analysis indicate that factors related to strengths and opportunities predominate.

Keywords: Co-Simulation, Modelling, Simulation, Delphi Method, Empirical survey

1. Introduction

Simulation-driven assessments and developments are key methods used in various fields in industry and academia such as energy systems, production industries and social sciences. Due to the increasing complexity of systems, market competition and specialization, evaluating the overall behavior of these

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systems at every stage of their development is becoming steadily more difficult, ranging from early *what-if* architectural analyses to detailed three dimensional simulations. In order to keep benefiting from the results of simulation-based analyses, new techniques are required to efficiently simulate the interactions between subsystems. There are two ways to achieve this end: (i) the entire system can be modelled and simulated with a single tool which is referred to as monolithic simulation; or (ii) established tools for the respective subsystems can be coupled in a so-called co-simulation.

As our knowledge of each subsystem matures, simulation tools become more specialized, accumulating years of research and practical experience in their respective domains. As such, the use of the co-simulation approach allows existing simulation tools to be leveraged. It has the potential to provide a quick and accurate way to realize holistic simulations by depicting interactions between subsystems while using the most appropriate simulators for each subsystem [1]. As a consequence, there has been an increasing number of applications of co-simulation across many domains [2, 3, 4, 5, 6, 7]

In co-simulation, the subsystem models are interconnected at their behavioral levels, through the traces computed by the corresponding simulation tools. To run a co-simulation, one needs a co-simulation scenario and an orchestrator algorithm [8]. The *co-simulation scenario* points to one or more simulation units, describing how the inputs and outputs of their models are related.

Each *simulation unit* is seen as a black box, capable of producing outputs and consuming inputs, according to the model it represents. To produce behavior, the simulation unit needs to have a notion of:

- a *model*, which is created by the modeller based on his knowledge of the system under study;
- a *solver*, which is part of the modeling tool used by the modeller that approximates the behavior of the model; and
- an *input approximation*, which approximates the inputs of the model over time, to be used by the solver; as well as
- *input reactivity* and *output reactivity*, which determine which inputs the simulation unit receives from the orchestrator.

The models of each simulation unit and their couplings (described by a co-simulation scenario) induce what we call an *implicitly coupled model* of the system under study. The *validity* of a co-simulation is related to the validity of the implicit coupled model, that is, how well the meaning of the model represents the dynamics of interest in the system under study. The *accuracy* of a co-simulation is related to how closely the results produced by the co-simulation match the meaning of the implicitly coupled model. The *orchestrator* is responsible for producing the results of a co-simulation. It initializes all the simulation units with the appropriate values, sets/gets their inputs/outputs, and coordinates their progression over the simulated time.

A previous state-of-the-art survey identified two main paradigms: *discrete event* (DE) and *continuous time* (CT) co-simulation. In discrete event co-simulation orchestration, the communication between simulation units is done using events. These units are characterized by their reactivity and transiency.

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Reactivity means that events can change the state instantaneously (within the same simulated time), and transiency means that events can cause other events to occur instantaneously. In Continuous Time co-simulation, ideally, the simulation units exchange their values continuously. The combination of CT and DEE paradigms lead to hybrid co-simulation. The co-simulation standard prescribes the communication interface and protocol between the simulation units and orchestrator. Well-known standards are: Functional Mock-up Interface (FMI [9]), High Level Architecture (HLA [10]) and DEVS [11].

Co-simulation is attractive because:
- the trace level is the simplest level at which any subsystem integration can be performed, and any dynamic model can be interpreted to produce such traces;
- each black box incorporates its own simulation algorithm, which is usually the most appropriate for its domain;
- the exchange of the black box models can be made without requiring their content to be disclosed, thereby protecting Intellectual Property (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 subsystem models, which leads to the central research question in co-simulation: *are the co-simulation results trustworthy?* This is not a new question, and the coupling of simulators can be traced back to multi-rate simulation techniques [12]. However, the black box nature of co-simulation makes it unique. For this reason, researchers have begun to address this challenge in the different domains in which co-simulation is applied.

To assess the importance of co-simulation in the scientific community, we conducted a keyword analysis and examined co-simulation related projects. The analysis was performed on Scopus with the keyword "co-simulation". Figure 1 shows that the number of citations grew in an almost linear fashion from 2000 to 2017. As it can be seen in Figure 2, most of the publications can be assigned to the fields of Engineering (40%) followed by Computer Science (25%) and Mathematics (11%). Table 1 gives an overview of prominent recent research projects related to co-simulation.

The extensive and scattered nature of the body of knowledge in co-simulation, prompted researchers to initiate surveys of the state of the art.

1.1. State of the Art

Co-simulation is now extensively used in industry and academia. This has motivated researchers to conduct survey work and examine fundamental concepts of co-simulation and the terminology used. A discussion of differences in terminology and an attempt to classify and structure co-simulation methods was made by Hafner and Popper [24]. The authors proposed several possibilities of classifying and structuring methods of co-simulation: (i) distinction by the State of Development, (ii) distinction by the field of application, (iii) distinction by the model description, (iv) distinction by numeric approaches and (v)
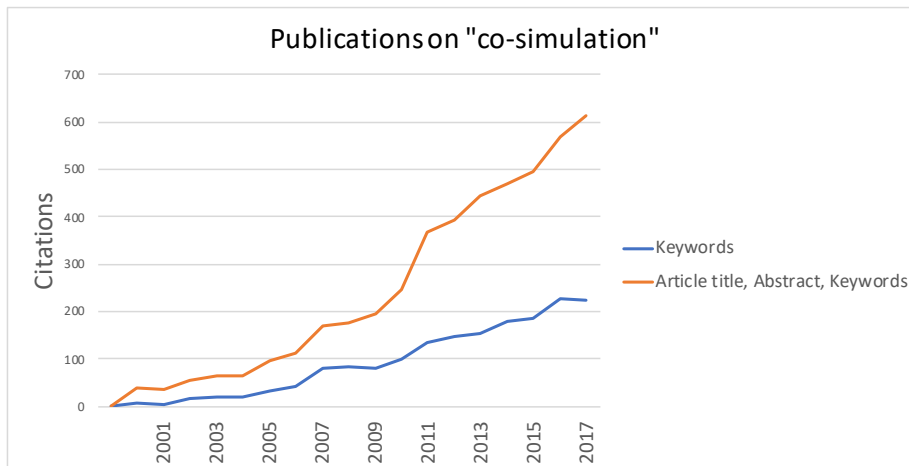
Figure 1: Publications that included the keyword "co-simulation"

distinction by Interfaces. Furthermore, a classification of multi-rate methods was proposed. Recognizing that co-simulation is not a new concept and that it has been applied in various different fields, Gomes et al. [8] reviewed co-simulation approaches, research challenges, and research opportunities. They applied a feature oriented domain analysis method [25] to help map the field. The main result was a feature model that could be used to classify the requirements of co-simulation frameworks and the participating simulators. They concluded that the main research needs were: finding generic approaches for modular, stable, valid and accurate coupling of simulation units and finding standard interfaces for hybrid co-simulation. Trcka and Wetter [26] reviewed (i) principles and strategies of co-simulation including a discussion of the terminology, (ii) the topic of stability and accuracy within co-simulation, (iii) tools and communication mechanisms that are used in prototypes, and (iv) verification and validation techniques. Based on numerical experimentation and case studies they conclude that the advantages of co-simulation are the flexibility by combining features from different tools; disadvantages were the difficulty of use and the required knowledge. Placing a focus on power systems, but still covering the fundamental concepts, Palensky et al. [27] highlighted the value of co-simulation for the analysis of the former. In a tutorial fashion, they go over the main concepts and challenges, providing a great introduction for new researchers in the field. To the best of our knowledge, these efforts are purely based on the existing literature and lack an empirical aspect.

1.2. Main Contribution

This work complements the existing surveys by providing the empirical aspect. We interviewed multiple experts from various fields in industry and academia as part of a two-stage Delphi study. As a result, the current challenges, research needs, and promising standards and tools were investigated
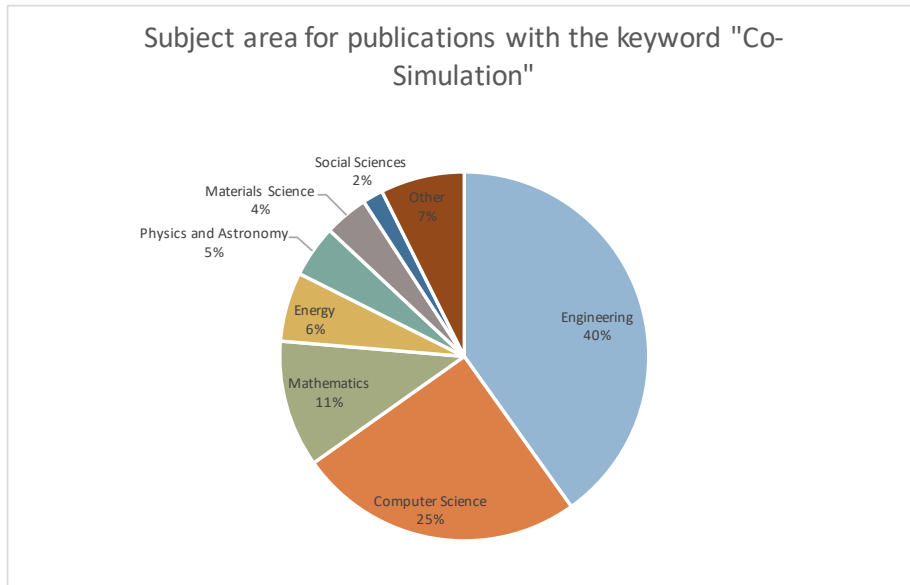
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Figure 2: Subject area for publications that include the keyword "co-simulation"

using qualitative and quantitative research methods. Some of the challenges identified by the experts indeed match the conclusions of the existing surveys. As such, the current work allowed us to rank the existing research according to their importance, as perceived by industry and academia. Furthermore, we present an analysis of the internal strengths and weaknesses as well as the external opportunities for and threats to co-simulation by combining a SWOT (strengths, weaknesses, opportunities and threats) analysis with the AHP (Analytic Hierarchy Process) resulting in an SWOT-AHP analysis, the results of which allowed us to gain a better understanding of the relative importance of the respective factors.

The findings in the present work:

- contribute to the structured and focused further development of various disciplines within the co-simulation community;
- can guide the efforts of the scientific community to address problems that are directly relevant to industry; and
- can serve as a practical guide by providing references to existing surveys, promising standards and tools for co-simulation.

The questionnaire as well as all quantitative answers from the second round are openly available at GitHub: https://github.com/GersHub/Survey-on-Co-Simulation - Survey-on-Co-Simulation and osf.io: https://osf.io/exu5w/.

A detailed discussion of the technical challenges goes beyond the scope of this work. Instead, we will provide the relevant references when appropriate.

The paper is structured as follows: In Chapter 2, we present a detailed presentation of the proposed method. Chapter 3 provides the results and discussion

Table 1: Excerpt of research activities in the field of co-simulation in recent years (not complete)

Project	Duration	Goals
COSIBA [13]	2000–2002	Formulate a co-simulation backplane for coupling electronic design automation tools, supporting different abstraction levels.
ODETTE [14]	2000–20003	Develop a complete co-design solution including hardware/software co-simulation and synthesis tools.
MODELISAR [15]	2008–2011	Improve the design of embedded software in vehicles.
DESTECS [16]	2010–2012	Improve the development of fault-tolerant embedded systems.
INTO-CPS [17]	2015–2017	Create an integrated tool chain for Model-Based Design of CPS with FMI.
ACOSAR [18]	2015–2018	Develop a non-proprietary advanced co-simulation interface for real time system integration.
OpenCPS [19]	2015–2018	Improve the interoperability between Modelica, UML and FMI.
ERIGrid [20]	2015–2020	Propose solutions for Cyber-Physical Energy Systems through co-simulation.
PEGASUS [21]	2016–2019	Establish standards for autonomous driving.
CyDER [22]	2017–2020	Develop a co-simulation platform for integration and analysis of high PV penetration.
EMPHYSIS [23]	2017–2020	Develop a new standard (eFMI) for modeling and simulation environments of embedded systems.

of the empirical survey and Chapter 4, the conclusion of the study.

2. Method and Rationale

In this section, we describe our methodology, the expert selection process, and how the answers were handled in detail. Furthermore, we describe how the quantitative analysis of the strengths, weaknesses, opportunities and threats (SWOT) of co-simulation was conducted.

2.1. Delphi Method

As a methodological foundation of this study, the Delphi method [28] was adopted. The Delphi method is an empirical research method that relies on the systematic compilation of knowledge from a selected group of experts [28, 29]. It fosters the exploration of problems that are characterized by an incomplete state of knowledge [30], a lack historical data, or a lack of agreement within the studied field, which makes it a perfect fit to apply to co-simulation [31]. The aim of applying the Delphi method is to arrive at a reliable shared opinion by means of a repetitive assessment process that includes controlled feedback of opinions [32]. 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" [33].

The Delphi study applied in the present work includes two rounds. The choice of rounds was justified by, for instance, Sommerville [34], who argued that the changes in the participants' views occurred in most cases during the first two rounds of the study and few insights were gained in further rounds. The quality of the Delphi process depends on the factors of creativity, credibility, and objectivity [35]. To address these quality criteria we followed acknowledged guidelines that have been provided by authors such as as those of [31, 32, 35]. The questions in the first round were selected based on the existing studies on

co-simulation (see Section 1.1) and the experience of the authors of the current study. Both rounds included qualitative (open-ended) and quantitative questions. In the first round, the majority of questions asked were qualitative, whereas in the second round, they were quantitative. This ensured that the topic could be introduced in a general way in the first round. To see why, note that if the first round had consisted mainly of quantitative questions, there would have been an increased risk of overlooking important factors or biasing the results. The qualitative questions asked in the first round only addressed findings that were common among survey papers referred to above. In these cases, expert opinions were used to evaluate the findings of the previous surveys and enable quantitative statements and comparisons to be made. The quantitative questions asked in the second round were mainly formulated based on the results of the first round and the findings reported in the recent literature (e.g., where contradictions were identified).

Regarding the number of experts, Clayton [36] indicated that fifteen to thirty experts with homogeneous expertise backgrounds or five to ten experts with heterogeneous backgrounds should be involved in a Delphi process, while Adler and Ziglio [37] argued that ten to fifteen experts with homogeneous expertise backgrounds could already be considered appropriate.

2.2. SWOT-AHP

The literature lacks studies that have been carried out to systematically investigate the advantages and disadvantages of co-simulation and relate them to each other. Thus, in the second round of the Delphi study, we conducted a quantitative SWOT analysis utilizing an Analytic Hierarchy Process. A SWOT analysis is an analytic technique used to analyze the internal strengths and weaknesses, as well as the external opportunities and threats of a project, product, person, or other item [38]. While a classical SWOT analysis may be used to pinpoint specific factors, the selected factors are not prioritized or weighted in terms of their relative importance. In practice, this complicates strategy development and means that the strategic planning process strongly depends on the individual judgments of the people involved. To overcome this drawback, we adopted an Analytic Hierarchy process (AHP) in our SWOT analysis. The goal of the use of this integrated SWOT-AHP method was to gain a better understanding of the relative importance of each factor. Therefore, experts were asked to make a pairwise comparisons and weighting of the respective factors in each category, as well as compare the categories based on a 9-point scale. Saaty [39] developed an AHP that is based on the eigenvalue method. The goal was to synthesize a pairwise comparison matrix and to get a priority for each factor in a group. In a first step, the relative priority of each factor in each group was calculated based on the average results of the pairwise comparisons. The result gained was the "local factor priority". In a second step, the "group priority" was calculated based on the average results of how experts assessed the priority of the individual groups. In a third step, the "global factor priority" of the respective factors was calculated by multiplying the local factor priority by the respective group priority. Details about the AHP method can be found

in [39]. In the first round of the Delphi study, we conducted a standard SWOT analysis. Relevant factors in the first round were selected based on an extensive literature study (see Section 1.1) and the experience of the authors. Experts were asked to select the three factors for each category that they considered the most important. To help validate the selected SWOT factors, an open-format question was included in each SWOT section, and experts were asked whether they considered any factors other than the ones we had selected as being more important. Based on these results, we selected the three most important factors per category for the second round, in which experts conducted the SWOT-AHP, performing a pair-wise comparison of all factors in the same SWOT field (i.e., stating the degree to which each factor of each pair was more important than the other). The experts then were asked to also compare the four SWOT groups themselves, while bearing in mind the three factors per group.

2.3. Expert selection and response rate

The Delphi method does not prescribe any particular way of selecting experts. We used a Knowledge Resource Nomination Worksheet (KRNW) as a framework [31]. The KRNW was proposed in [40] as a general criterion that could be used to sample an expert panel by classifying the experts before selecting them in two iteration steps, to avoid overlooking any important class of experts. This framework consists of the following five steps, detailed below: (1) preparation of the KRNW; (2) population of the KRNW; (3) nomination of additional experts; (4) ranking of experts; and (5) invitation of experts.

In Step (1), we classified the experts according to whether they worked in *academia* or *industry*, as both perspectives were considered essential. Then, in Step (2), the *academia* category was populated based on a keyword-based search in the literature on the state of the art in co-simulation (see Section 1.1). The *industry* category was populated based on the same keyword-based search (i.e., if they had (co-)authored a publication) and the experience of the authors. Afterwards, in Step (3), both categories were expanded based on the suggestions received after contacting the initial list of experts. In Step (4), the ranking of experts was done using the number of publications in the field of co-simulation, which was obtained from Scopus (see Section 2.5). In Step (5) the final group of experts was invited to take part in the Delphi study. Fifteen experts were contacted for the first round; after receiving a final reminder by email, twelve completed questionnaires were returned. The response rate for the first round was, thus, 80 %. In the second round, we contacted seventy persons; after receiving a final reminder by email, 53 completed questionnaires were returned. The response rate for the second round was, thus, 76 %. We can safely state that a significant share of representatives from co-simulation experts were involved in the analysis [36, 37].

Experts from industry who took part in the survey worked in the following sectors: energy Systems (5), software development (7), mobility (4), engineering services (1), system engineering (1), avionics, railways (1). Experts from academia who took part in the survey work in the following fields: energy-related applications (8), software development (6), automotive (3), computer

Science (2), maritime (1), system Engineering (1), numerical mathematics (1), system modelling and verification (1) and formal methods (1). Some experts did not provide information about their field or sector.

Table 2 summarizes the aim and approach of each round and provides the number of participants per category.

Table 2: Summary of method.

Round	Aim	Approach	Participants			
			A	I	ND	Total
1	Identification of research needs, SWOT factors, limitations and possible extension.	Qualitative	7	2	3	12
2	Evaluation of the result from the first round and development of in-depth discussions on the key aspects. Test on convergence the identified factors, themes and scenarios	Semi-quantitative	24	19	10	53

2.4. Presentation of the results

A content analysis was performed following the method of Mayring to analyze the qualitative answers [41]. Authors of scientific literature have conducted controversial discussions about which statistical measures are suitable for the interpretation of results of a survey, such as Likert-scales. Hallowell and Gambatese [42] argued that results should be reported in terms of the median rather than the mean, because the median response is less likely to be affected by biased responses. The median is the middle observation in a sorted list of data, separating the upper half from the lower half of a dataset. Sachs [43] argued that the interpolated median is more precise than the normal median, because it is better to consider the frequencies of answers within one category in comparison to all answers. The interpolated median is used to adjusts the median upward or downward within the lower and upper bounds of the Median (M), in the direction in which the data are more heavily weighted. The interpolated median (IM) is calculated as follows:

$$IM = \begin{cases} M & \text{if } n_2 = 0, \\ M - 0.5 + \frac{0.5 \cdot N - n_1}{n_2} & \text{if } n_2 \neq 0 \end{cases} \quad (1)$$

where N is the total number of responses to the question, n_1 is the number of scores strictly less than M and n_2 is the number of scores equal to M. In order to provide a transparent presentation of the results, (i) all results are displayed in detail in a bar chart in the appendix and (ii) in Section 3, all results are discussed using mean, median and interpolated median values. Remarkable agreement or differences among experts (or groups of them) are highlighted when identified.

2.5. Threats to validity and limitations of the study

Detailed discussion about the threats to validity in Delphi studies can be found in [44]. The selection of experts from academia was done based strictly on the number of publications listed in Scopus. There is an ongoing discussion about how to compare the scientific impact among researchers. While some indices are well-suited for comparing researchers within the same field, this is not

the case for comparing different fields. Since co-simulation is an interdisciplinary field of research, the selection of experts in this work can be seen as a threat to validity. The ranking of experts from industry was done based on the number of publications listed in Scopus. In addition, we selected experts from industry who we knew have been working with co-simulation for a long time and who have theoretical and practical knowledge in the field of co-simulation. It can be regarded as a limitation regarding the representativity of the results; however, the responses of the experts indicated that they indeed were well experienced. This selection process ensured that also experts from industry whose focus is not on scientific publishing participated in the study.

3. Results and Discussion

In this section, we present the key findings from the Delphi study and the SWOT-AHP analysis. In the results below, most questions are multiple choice, and the options available were collected during the first round of the Delphi study. To accommodate for additional answers, an extra open field was provided. These open answers, where applicable, are displayed under the *Other* category. All questions of the questionnaire (including questions not addressed in this paper) are openly available (https://github.com/GersHub/Survey-on-Co-Simulation).

3.1. Simulator and Co-simulation Characterization

In order to analyze the purpose for which experts used co-simulation, experts were asked to select the properties that apply to the simulators with which they have worked in co-simulation. As can be seen in Figure 3, the majority of the simulators being used in co-simulation represented sets of differential equations. Still, between 18% and 25% of the experts used simulators as "specialized in networks", as "specialized in software controllers", as "a dedicated piece of hardware" or as "receiving input from a human machine interface". The same figure indicates that Finite Element (FE) subsystems represent a minority among the experts interviewed. This result is surprising because FE modeling is one of the fields where co-simulation has been applied extensively to enable parallel computation of the solution (e.g., see [45]).

The properties that were not predefined in the questionnaire represent a minority of answers: one expert used co-simulation to prove a theorem and another, to solve partial differential equations using finite volume methods. These results indicate that the first round of the Delphi study was successful in that the uses of the simulators could be characterized, and determine that co-simulation was used for many different applications.

3.2. Dissemination channels

To identify the main dissemination channels, experts were asked to name the three most important scientific sources used to disseminate their work. The results are shown in Figure 4. The Modelica Conference was cited as by far the
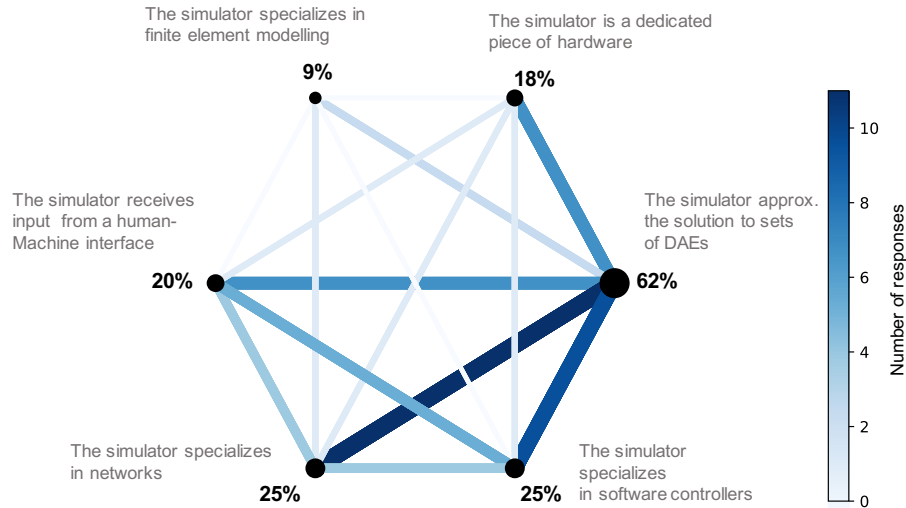
Figure 3: Answers to the question: "which properties apply to the simulators . . . ?". Each node represents a property. The size of each node is proportional to the number of positive responses to the corresponding property. Moreover, the thickness of the edge-connections nodes x to nodes y indicates that the same expert gave positive reply to both property x and y. Note that the latter does not imply (and neither neglect) the different properties to apply in one and the same co-simulation.

most important channel for experts used to disseminate their work. The FMI has been one of two key topics in this conference, suggesting that this result is co-related with the fact that the FMI is considered to be the most promising standard for co-simulation (see Section 3.3). The dissemination channels suggested by the experts are highly heterogeneous, which underlines the assumption that co-simulation is indeed a multi-disciplinary research field.

3.3. Established Standards and Tools

To identify promising standards for continuous time, discrete event and hybrid co-simulation, we asked experts (i) to give their opinion on widely accepted standards and describe (ii) what standard they used for co-simulation. We would like to point out that no generally valid statements can be derived here as to which standards are widely used in industry and academia; the sample size is too small for this and the influence of possible biases on the selection of experts is too high. The results are summarized in Figure 5.

As can be seen in the figure, the FMI standard is by far the most commonly used standard for any kind of co-simulation.

While the responses for "widely accepted standards" and "standards which experts use" were similar for continuous time and hybrid co-simulation, a different picture emerged for discrete event co-simulation. FMI was described as
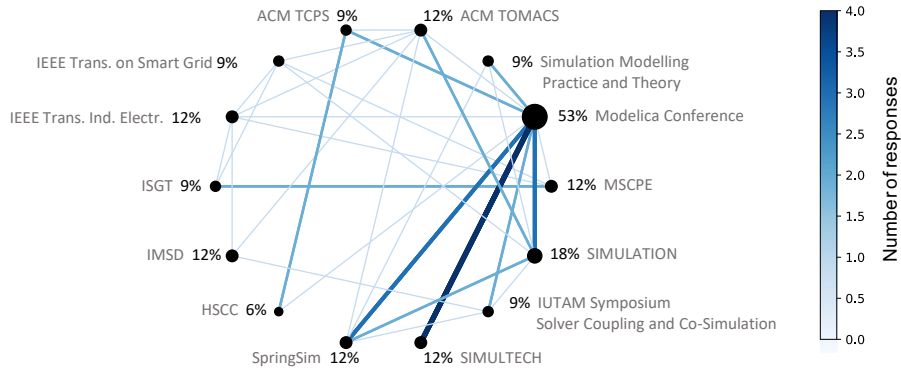
Figure 4: Experts were asked to mark the three most important scientific sources they used to disseminate their work. The numbers next to the nodes correspond to the ... % of positive responses; the size of the nodes is also proportional to number of positive responses. The statements upon which the respective experts agreed were connected. MSCPE = Workshop on Modeling and Simulation of Cyber-Physical Energy Systems; ISGT = IEEE Conference on Innovative Smart Grid Technologies; IMSD = International Conference on Multibody System Dynamics; HSCC = Conference on Hybrid Systems: Computation and Control. Conferences mentioned only once by experts are not shown; these included the Conference of the IEEE Industrial Electronics Society, IEEE transactions on power delivery, IEEE Power & Energy Society General Meeting, International Association of Applied Mathematics and Mechanics, Problems in Science and Engineering, European Community on Computational Methods in Applied Sciences and Workshop on Co-simulation of Cyber Physical Systems.
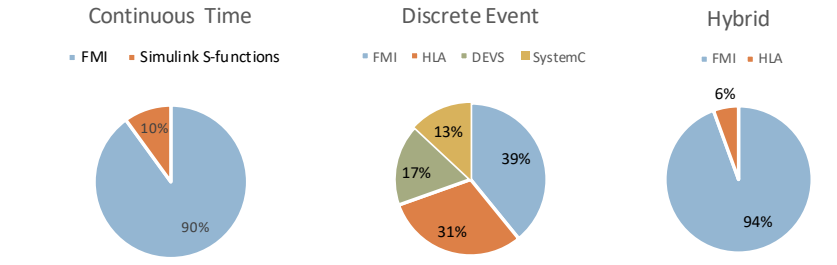
widely accepted for discrete event co-simulation by 39 % of the experts, however, 68 % of the experts used FMI for discrete event co-simulation. A dedicated empirical study, similar to the one presented here, was performed to identify challenges/barriers to the adoption of the FMI standard [46]. The main results of that study are summarized in Table 3.

In addition to promising standards, experts were asked which tools they used for co-simulation. The most common tools used for continuous time co-simulation were Modelica tools and Matlab/Simulink. The use of Modelica tools was cited by 40 % of the experts and about 25 % of the experts mentioned that they used Matlab/Simulink. For discrete event and hybrid co-simulation, no tool was significantly more frequently mentioned than others. The detailed results can be found in the Appendix (Tables 9, 10 and 11). While only seven different tools were listed for CT co-simulation, thirteen were listed for DE, twelve for hybrid co-simulation.

3.4. Current challenges

In the first round of the Delphi study, experts commented on current challenges. Based on these responses and the state-of-the-art surveys, we formulated several statements regarding personal experiences. In the second round of the

In your opinion, is there a widely accepted standard for [...] Co-Simulation?

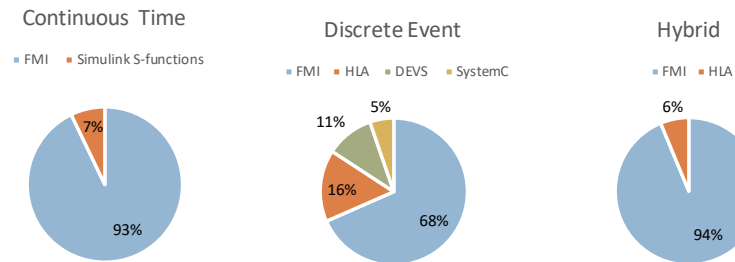**What standard do you use for [...] Co-Simulation?**

Figure 5: Widely accepted and used standards for co-simulation. Depending on the sub figure, the brackets [...] correspond to "Continuous Time", "Discrete Event" or "Hybrid"

Delphi Study, we posed these statements as questions (e.g., "Have you experienced..."). The experts then used a 6-point Likert scale that ranged from from 1 = "very frequently" to 6 = "never". Figure 6 summarizes the responses sorted according to how often experts experience each challenge. Table 5 in the Appendix shows the Mean, Median, and Interpolated Median for all responses. A detailed discussion of the individual challenges goes beyond the scope of this survey. However, appropriate references are provided next to each challenge in Table 5.

Most challenges (all except simplistic extrapolation functions and difficulties in choosing the correct orchestration algorithm) were assessed by the experts with an interpolated median value greater or equal to four, implying at least occasional occurrence. The experts, thus, confirm the challenges identified in the first round and from the state of the art. The most acknowledged challenge is related to practical aspects. These include: faulty/incomplete implementations of the FMI standard, ambiguities/omissions in the specification and documentation of the FMUs, etc... Some of these have been documented in the state of the art (e.g., [47, 48, 49, 50]). This is not a surprising result, as the FMI Standard specification is in its infancy, and we expect that upcoming versions will address some of these issues. Moreover, the community has produced tools

Table 3: Expert assessment of current barriers for FMI. Based on a Seven-point Likert scale. Modified from [46]. Score: Entirely agree (7); Mostly agree (6); Somewhat agree (5); Neither agree nor disagree (4); Somewhat disagree (3); Mostly disagree (2); and Entirely disagree (1).

|	Mean	Median	Interp. Median
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
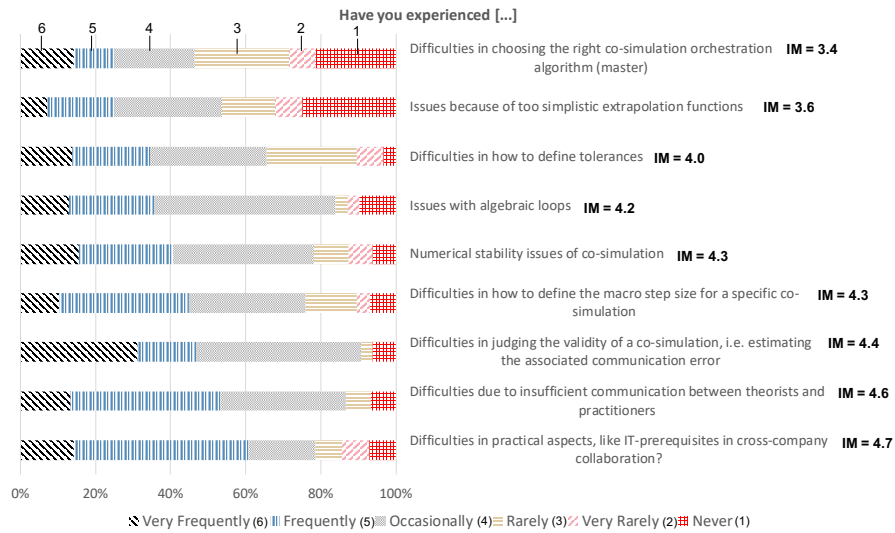
Figure 6: Experts' assessments: Current challenges. IM = Interpolated Median. Score: Very Frequently (6) Frequently (5) Occasionally (4) Rarely (3) Very Rarely (2) Never (1). Each answer is assigned a numeric value and these values are used for the calculation of the Interpolated Median.

and examples to validate FMI implementations, available for free [1].

The difficulties encountered when judging the validity of a co-simulation present pertinent challenges, already important in the simulation field [51, 52] and aggravated by the black-box nature of co-simulation.

Many experts identified having difficulty choosing the right macro step size, defining tolerances (macro step size and tolerances are execution parameters)

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[1] https://fmi-standard.org/

and with numerical stability. From these responses, we conclude that there is a need for frameworks that provide suitable suggestions to ease the choices for the user. In particular, because of the high response count for the lack of communication between theorists and practitioners, we assume that many users have significantly less know-how in the areas in practice, than the experts interviewed in this work.

3.5. Research needs

Experts were asked about research topics in the field of co-simulation that have not received enough attention up until now. Figure 7 summarizes the response count on a 7-point scale from "Entirely Disagree" to "Entirely agree". Table 6 in the Appendix shows the Mean, Median and Interpolated Median for all responses. A detailed discussion of the individual research needs goes beyond the scope of this survey. However, appropriate references are provided next to each research need in Table 6.

Most research needs (all except simulator black boxing and IP protection) are assessed by the experts with a interpolated median value greater 4.5, corresponding to at least "Somewhat agree". Seven research needs were rated with an interpolated median score of greater or equal to 5.5 which corresponds to at least "Mostly agree". The experts thus confirm the research needs identified in the first round and from the existing surveys.

In the context of hybrid co-simulation, an expert mentioned that there is only limited awareness about the problems that can arise in hybrid co-simulation; in many cases, it is difficult for user to understand whether problems arise due to shortcomings in standards, tool implementation, or usage.

The fact that many experts agree that uncertainty quantification and propagation techniques need to be developed suggests that users want co-simulation to be used as part of optimization loops and/or sensitivity studies, which means that researchers needs to adapt traditional sensitivity analysis (e.g., [53, 54]) to co-simulation.

Overall, addressing these challenges will involve understanding what information about the simulation units can be disclosed without sharing IP, and how can traditional simulation analysis techniques be adapted to work with partial views of the sub-models.

Equally important is how to standardize co-simulation in a way that enables researchers and practitioners to take advantage of the solutions to these challenges. As one expert stressed, a fundamental question that standardization committees have to ask is: is the intention of a co-simulation standard to support the same flexibility as traditional monolithic simulation, or is the intention to couple large subsystems? Allowing for more flexibility makes standards more complex, and difficult to implement. This suggests that in the upcoming years, one of the challenges will be to balance the trade-off between flexibility and simplicity.
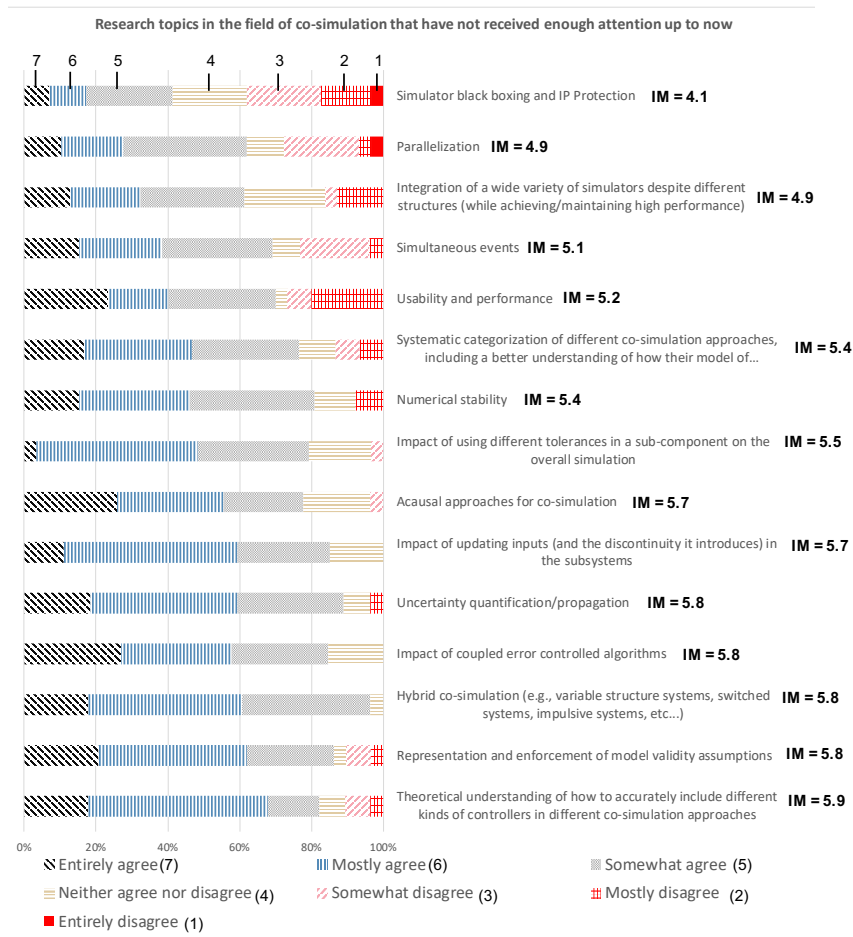
Figure 7: Experts' assessments: Research needs. IM = Interpolated Median. Score: Entirely agree (7) Mostly agree (6) Somewhat agree (5) Neither agree nor disagree (4) Somewhat disagree (3) Mostly disagree (2) Entirely disagree (1). Each answer is assigned a numeric value and these values are used for the calculation of the Interpolated Median.

3.5.1. Miscellaneous

This subsection presents results of the Delphi study that do not fit into the previous subsections. Experts were asked the extend to which they agreed on several statements. The 7-point Likert scale was used to measure the responses (Entirely agree =7 to Entirely disagree = 1). Experts mostly agreed with the statement *"For academia it is difficult to experiment with different co-simulation approaches as there is a huge learning curve: in terms of learning the specification and also gaining access to models as well as being able to make changes to existing approaches and test new ideas"* ($IM = 5.8$) and somewhat agreed with the statements *"A clearer categorization of different co-simulation approaches*

would help for your particular field of work" ($IM = 5.1$) and *"The major benefit of co-simulation is to increase performance, when compared to a monolithic simulation"* ($IM = 4.7$); they neither agreed nor disagree with the statement *"A acausal approaches can boost the use of co-simulation in your field"* ($IM = 4.3$).

3.6. SWOT-AHP

The results of the SWOT-AHP analysis are presented in Table 4 and in Figure 8. The factors for each group are given along the lines in the four sectors. The lengths of the lines indicate the group priority and, respectively the relative overall importance of the four SWOT-groups. The three circles per group indicate the global factor priorities; the longer the distances between the respective group/factor and the origin, the higher the overall importance assigned this group/factor.

Table 4: Result SWOT-AHP

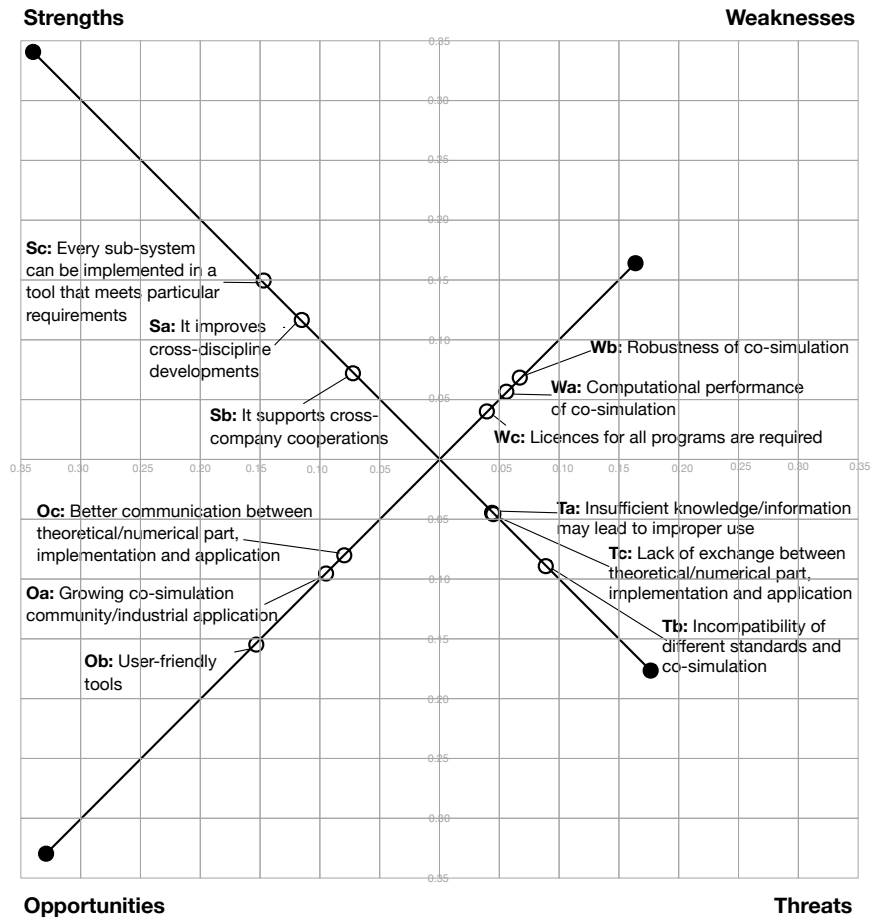| SWOT Factors	Consist. Ratio	group priority	local priority (rank)	global priority (rank)
Strengths (internal)	0.085	0.34		
Sa: It supports cross-discipline developments			0.35 (2)	0.117 (3)
Sb: It supports cross-company cooperations			0.21 (3)	0.072 (7)
Sc: Every sub-system can be implemented in a tool that meets the particular requirements for the domain, the structure of the model and the simulation algorithm			0.44 (1)	0.148 (2)
Weaknesses (internal)	0.013	0.16		
Wa: Computational performance of co-simulation compared to monolithic simulation			0.34 (2)	0.056 (9)
Wb: Robustness of co-simulation compared to monolithic simulation			0.41 (1)	0.067 (8)
Wc: Licenses for all programs are required to couple different simulation programs			0.24 (3)	0.039 (12)
Opportunities (external)	0.003	0.33		
Oa: Growing co-simulation community/growing industrial adoption			0.29 (2)	0.094 (4)
Ob: User-friendly tools (predefined master algorithms, integrated error estimation, sophisticated analysis to determine best parametrization of solvers and master algorithms)			0.47 (1)	0.153 (1)
Oc: Better communication between theoretical/numerical part, implementation and application/industry			0.25 (3)	0.080 (6)
Threats (external)	0.003	0.18		
Ta: Insufficient knowledge/information of user in co-simulation may lead to improper use			0.28 (3)	0.088 (5)
Tb: Incompatibility of different standards and co-simulation approaches			0.41 (1)	0.043 (11)
Tc: Lack of exchange/cooperation between theoretical/numerical part, implementation and application/industry.			0.31 (2)	0.044 (10)

Strengths   **Weaknesses**

Sc: Every sub-system can be implemented in a tool that meets particular requirements

Sa: It improves cross-discipline developments

Sb: It supports cross-company cooperations

Wb: Robustness of co-simulation

Wa: Computational performance of co-simulation

Wc: Licences for all programs are required

Oc: Better communication between theoretical/numerical part, implementation and application

Oa: Growing co-simulation community/industrial application

Ob: User-friendly tools

Ta: Insufficient knowledge/information may lead to improper use

Tc: Lack of exchange between theoretical/numerical part, implementation and application

Tb: Incompatibility of different standards and co-simulation

Opportunities   **Threats**

Figure 8: SWOT-AHP for the research needs. Black dots indicate group priorities, circles indicate global factor priorities.

The results of the SWOT-AHP analysis indicate that factors for strengths and opportunities predominate. The four factors with the highest global priorities fell within the Strengths and Opportunities group. The factor with the highest global priority is the external opportunity of "user-friendly tools including predefined master algorithms, integrated error estimation, etc.". The factor with the second-highest global priority is the internal strength that "sub-systems can be implemented in a tool that meets the particular requirements for the domain, the structure of the model and the simulation algorithm". The factor with the third-highest global priority is the internal strength that "co-simulation supports cross-discipline developments". Some experts mentioned additional SWOT factors. As a strength, some experts mentioned that "parallel modeling and simulation can reduce the overall modeling and simulation time".

Another strength identified was "co-simulation approaches supports modularity and the reuse of components." An expert stated the "lack of sufficiently strong theory" as a weakness of co-simulation. In the group opportunities, an expert mentioned the "integration of tools for the application of formal methods." One expert pointed out that a threat could be that "some big companies may be actively against the widespread use of co-simulation".

An interesting outcome is that the groups of Strengths and Opportunities were reviewed as much more important than the Weaknesses and Threats. This was due to the priority assigned to the first two groups, which was approximately twice as high as the latter two. The consistencies of the pairwise comparisons was checked. All consistency ratios are below 0.1. It can be concluded, that the results are consistent.

4. Conclusions and outlook

The present paper presents an expert assessment on co-simulation, adressing the social and empirical aspects and placing a focus on promising standards and tools, current challenges and research needs. As a methodological foundation of this study, the Delphi method was adopted. Furthermore, a quantitative analysis of the SWOT of co-simulation utilizing the Analytic Hierarchy Process was conducted. The authors consider the following findings from the empirical data as the most important:

- Experts consider the FMI standard as the most promising standards for continuous time, discrete event and hybrid co-simulation;
- Experts frequently have difficulties dealing with practical aspects, like IT-prerequisites in cross-company collaboration, and encounter problems due to insufficient communication between theorists and practitioners.
- The most important research needs identified by experts are: (i) theoretical understanding of how to accurately include different kinds of controllers in different co-simulation approaches, (ii) validity aspects, (iii) hybrid co-simulation (iv) accuracy aspects and (v) acausal approaches;
- The highest ranked difficulty relates to practical aspects while the highest ranked research need related to theoretical understanding. This is not a contradiction; this insight may help for making co-simulation wide-spread;
- The results of the SWOT-AHP analysis indicate that factors for strengths and opportunities predominate. The experts assign the highest important to the need for user-friendly tools including predefined master algorithms, integrated error estimation, etc.

Statistical tests were conducted to determine differences in the perceptions of experts from industry and academia regarding the current challenges and open research topics; no significant difference were observed. We refrained from testing more complex hypotheses in this study, due to the number of answers and the non-probability sampling approach taken. However, the results of this study can be used as a basis for a follow-up, purely deductive study in which various hypothesis can be tested with a larger sample.

It is our hope that the results of this study will increase transparency and facilitate the structured development of co-simulation standards and tools.

Acknowledgement

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6. Appendix

Table 5: Experts' assessments: Current challenges. Score: Very Frequently (6) Frequently (5) Occasionally (4) Rarely (3) Very Rarely (2) Never (1).

	Mean	Median	Interp. Median
Difficulties in practical aspects, like IT-prerequisites in cross-company collaboration.	4.7	5.0	4.7
Difficulties due to insufficient communication between theorists and practitioners.	4.4	5.0	4.6
Difficulties in judging the validity of a co-simulation.	4.6	4.0	4.4
Difficulties in how to define the macro step size for a specific co-simulation [55, 56, 57].	4.3	4.0	4.3
Numerical stability issues of co-simulation [58, 8, 59].	4.4	4.0	4.3
Issues with algebraic loops [60, 57].	4.2	4.0	4.2
Difficulties in how to define tolerances.	4.3	4.0	4.0
Issues because of too simplistic extrapolation functions.	3.5	4.0	3.6
Difficulties in choosing the right co-simulation orchestration algorithm (master).	3.6	3.0	3.4

Table 6: Experts assessments: Research needs. 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	Interp. Median
Theoretical understanding of how to accurately include different kinds of controllers in different co-simulation approaches	5.5	6.0	5.9
Representation and enforcement of model validity assumptions [51, 52]	5.6	6.0	5.8
Hybrid co-simulation (e.g., variable structure systems, switched systems, impulsive systems, etc...) [48, 8]	5.8	6.0	5.8
Impact of coupled error controlled algorithms [56, 61]	5.7	6.0	5.8
Uncertainty quantification/propagation [62, 63]	5.6	6.0	5.8
Impact of updating inputs (and the discontinuity it introduces) in the subsystems [58, 64].	5.6	6.0	5.7
Acausal approaches for co-simulation [65]	5.6	6.0	5.7
Impact of using different tolerances in a sub-component on the overall simulation [66]	5.3	6.0	5.5
Numerical stability [67, 68]	5.3	5.0	5.4
Systematic categorization of different co-simulation approaches, including a better understanding of how their model of computations and requirements overlap and differ [69]	5.2	5.0	5.4
Usability and performance	4.9	5.0	5.2
Simultaneous events [70]	5.0	5.0	5.1
Integration of a wide variety of simulators despite different structures (while achieving/maintaining high performance) [71]	4.8	5.0	4.9
Parallelization [72, 73]	4.6	5.0	4.9
Simulator black boxing and IP Protection [9]	4.1	4.0	4.1
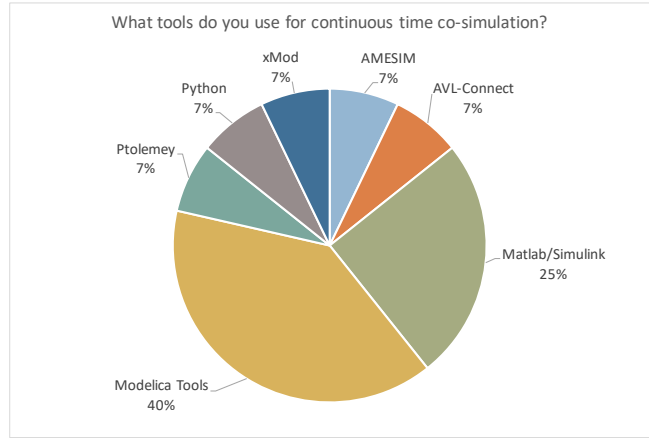
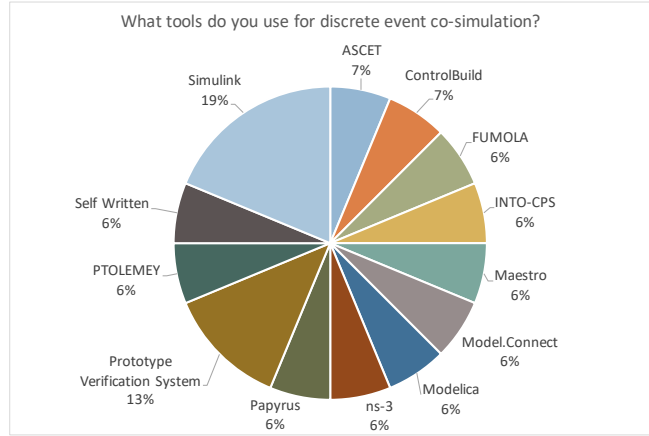Figure 9: Tools that experts use for continuous time co-simulation

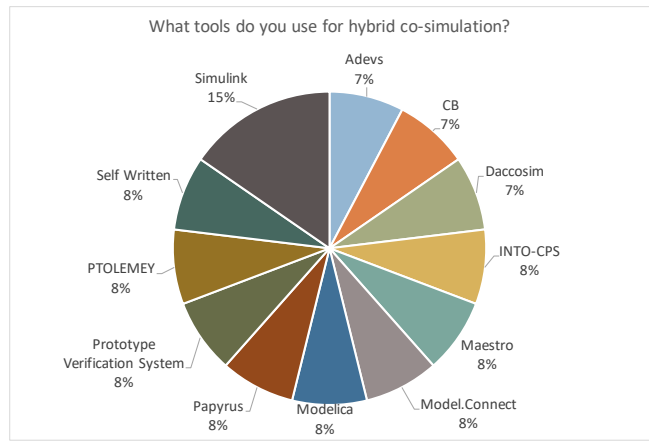Figure 10: Tools that experts use for discrete event co-simulation

Figure 11: Tools that experts use for hybrid co-simulation.