

Co-Simulation - An Empirical Survey: Applications, Recent Developments and Future Challenges

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SNE 30(2), 2020, 73-76, DOI: 10.11128/sne.30.sn.10516
 Received: December 5, 2019 (Selected MATHMOD 2018 Post-conf. Accepted: Publ.; Accepted: January 20, 2020
 SNE - Simulation Notes Europe, ARGESIM Publisher Vienna, ISSN Print 2305-9974, Online 2306-0271, www.sne-journal.org

Abstract. This article describes the first results of an empirical survey on co-simulation conducted with over 50 experts in this field. In the last decades, co-simulation has become an important tool to meet challenges emerging from the increasing complexity of systems and the need for efficient collaboration between experts in different disciplines. However, research on this topic has been motivated by varying fields of interest and developed with different perspectives on application and thus lead to different definitions and emphases within this topic. The present survey aims to clarify some of these different perceptions and open research fields.

Introduction

In recent decades, simulation-driven development has increasingly become established as a central method in industry and academia. This is leveraged by computational advances, like the recent emergence of equation-based modelling languages, which offers new possibilities compared to block diagram modelling using imperative programming languages [16]. Classically, systems are modelled in a single tool, which is referred to as monolithic approach. With the increased complexity of systems and the need for linking several domains in one

model, monolithic approaches have restrictions: sometimes it is not possible to simulate a complex system in a single tool, but even if it is possible, very often there are more suitable tools available for different subsystems. Ideally, every subsystem is modelled in a tool that meets the particular requirements for the domain and the structure of the model. Thus, the need for coupling different tools is a pragmatic one. Co-simulation is an approach to enable a simulation of complex single or multi-domain systems that consists of at least two subsystems (modelled in different tools) which solve coupled (algebraic) differential systems of equations ([5]). An overview of co-simulation approaches and tools, research challenges, and research opportunities are presented e.g. in the references [12, 1, 8, 5, 13]. The proposed empirical survey aims to merge different views of heterogeneous communities which are working in the field of co-simulation, on the state of the art, research gaps and future challenges.

1 Method

As a methodological foundation of the empirical survey, the Delphi method is adopted. The Delphi method is a forecasting technique that bases on the collection and compilation of expert knowledge from a panel of experts in a multi-stage process [3, 6]. It fosters group communication which is intended to deal with complex problems, particularly for the case where there is insufficient knowledge, lack of historical data, or lack of agreement found within the studied field [9]. The Del-

phi method is also conceived to be useful particularly for solving interdisciplinary research problems in a heterogeneous environment [11]. Moreover, it enables determining probable future scenarios. We aim at integrating at least 30 experts in our Delphi study, because despite the lack of a mandatory minimum requirement, [2], for instance, states that 15-30 participants are adequate for studies involving experts with a homogeneous expertise background. For selecting the sample of participants, a Knowledge Resource Nomination Worksheet (KRNW) is used as a guideline [4, 9]. The Delphi study forms two rounds. The first round comprises a mix of open-ended and closed-ended questions. The second round includes only closed-ended questions that are formulated based on the results of the first round. In addition to these standard questions, an additional quantitative analysis of the strengths, weaknesses, opportunities and threats (SWOT) of co-simulation utilizing the Analytic Hierarchy Process (AHP) is conducted. The SWOT-AHP method was introduced by [7] to increase the effectiveness of a primary SWOT analysis as a decision-making tool [10]. In this study, the SWOT-AHP method is utilized to enrich the results of the Delphi study by providing an additional and new perspective on the current state of co-simulation. The questionnaire for the first round of the Delphi study consisted of four parts:

1. *The roots of co-simulation.* This includes questions about different origins for co-simulation, concepts, wording and scientific and industrial communities.
2. *Theoretical questions.* Included are questions regarding the state-of-the-art, research gaps and open issues within continuous, discrete and hybrid co-simulation.
3. *Functional Mock-Up Interface (FMI).* Since FMI is already widely used and it is a promising candidate to become the standard for industry and academia, a section with specific FMI related questions was designed.
4. *Questions related to an overall SWOT analysis of co-simulation.*

At this stage of the survey, the first round of interviews and the expert selection for the second round have both been completed; more than 40 experts have already committed to participate in the second round.

2 Preliminary results

In the first round of interviews, experts had to select three factors for the categories 'Strengths', 'Weaknesses', 'Opportunities' and 'Threats'. In the following, we present the results for the pre-selection of SWOT factors in hierarchical order.

Strengths:

1. 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.
2. Cross-company cooperation is supported (e.g., suppliers and system integrators can exchange virtual "trial components" before signing contracts).
3. 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.

Weaknesses:

1. Computational performance of co-simulation compared to monolithic simulation.
2. Robustness of co-simulation compared to monolithic simulation.
3. Licenses for all programs are required to couple different simulation programs.

Opportunities:

1. Growing co-simulation community / growing industrial adoption.
2. Better communication between theoretical/numerical part, implementation and application/industry.
3. User-friendly tools (pre-defined master algorithms, integrated error estimation, sophisticated analysis to determine best parameterization of solvers and master algorithm).

Threats:

1. Insufficient knowledge/information of users in co-simulation may lead to improper use (e.g. wrong or missing error estimation, stability issues etc.).
2. Lack of exchange/cooperation between theoretical/numerical part, implementation and application/industry.

3. Incompatibility of different standards and co-simulation approaches.

In addition, the experts were asked to name established standards or promising candidates for standards in co-simulation for continuous time, discrete event and hybrid co-simulation. The results show that the Functional Mockup Interface is considered the most promising standard in all three categories (see Figure 1).

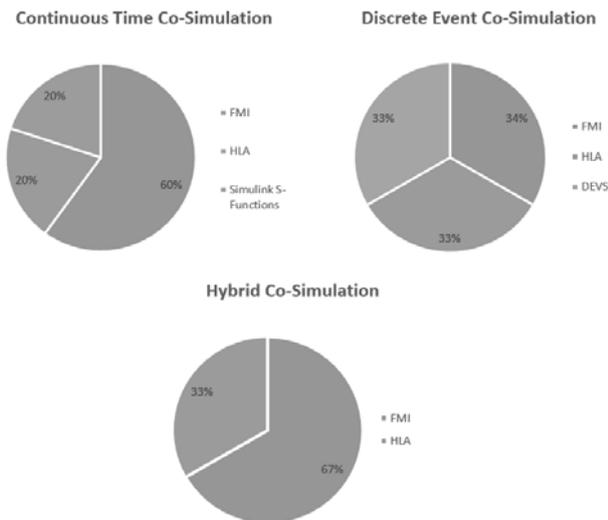


Figure 1: Established standards for co-simulation.

The experts' answers regarding their personal experience of difficulties with co-simulation are summarized in Figure 2.

Co-simulation is an omnipresent topic with ever-varying challenges and openings for new research. An assessment of currently open research fields by the participating experts is shown in Figure 3.

3 Conclusion

The first results of this study confirm the assumption that depending on the primal discipline and field of application, research on co-simulation exhibits different perceptions of the definition, specific focus and importance of challenges as well as open research questions in co-simulation. However, commonalities emerge for certain problems and promising standards, which are to some extent already worked on by experts from different disciplines in international cooperation. Final results of the survey can be found in [14] and [15].

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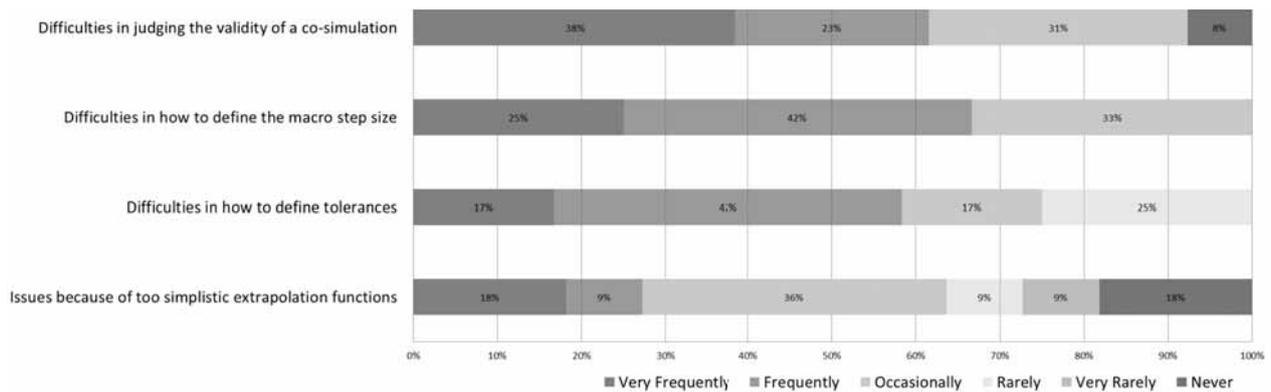


Figure 2: Experts' personal experience with co-simulation.

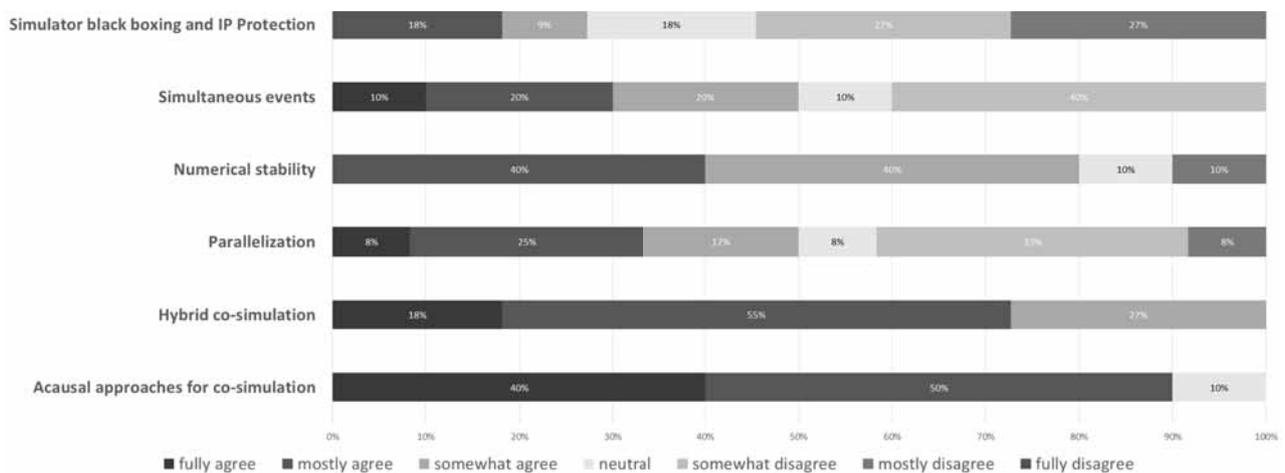


Figure 3: Open research fields in the area of co-simulation.

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