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TEN YEARS OF THE HYBRID SIMULATION TRACK: REFLECTIONS AND VISION FOR THE FUTURE

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ABSTRACT

The Hybrid Simulation (HS) track was included in the Winter Simulation Conference (WSC) proceedings as a full conference track for the first time in 2014. A decade has passed since that inaugural track, and HS research and practice has seen impressive advancements during this time. This paper, based on a high-level review of the published works in the last ten years of the HS track, reflects on its successes and challenges and sets the scene for the future of the field. The paper is authored by the HS track organizers, both past and present, who report on the track's history, the nature of HS applications, the modeling tools and software available, as well as implementation challenges and the users' perspective. Finally, the paper discusses the future of HS.

1 INTRODUCTION

The term Hybrid Simulation (HS) is normally defined as the use of two or more simulation methods in a combined fashion to model systems of interest (Brailsford et al., 2019). For clarity, the three main methods are Discrete-event Simulation (DES), Systems Dynamics (SD), and Agent Based Simulation (ABS). In recent years, there has been an increase in the use of HS, as well as significant theoretical advancements, the latter mainly through the development of HS frameworks, e.g., Nagadi et al. (2018), Farsi et al. (2019) and Nguyen et al. (2024). This has led to several literature reviews on HS, e.g., Scheidegger et al. (2018), Brailsford et al. (2019), dos Santos et al. (2020), Fakhimi et al. (2023) and Kar et al. (2024). An important publication venue for HS studies is the HS track of the Winter Simulation Conference (WSC). This article reflects on the developments in the HS field as these are manifested in the 10-year history of the HS track and presents the vision for the future.

The paper is structured as follows. In Section 2, Navonil Mustafee (NM) discusses the history of the track. Tillal Eldabi (TE) gives an overview of the nature of the HS application in Section 3. Modeling tools and software for HS are analyzed in Section 4 by Anastasia Anagnostou (AA). In Section 5, Antuela Tako (AT) discusses issues around HS implementation and looks at the user perspective. Sally Brailford (SB) presents her views on the future of HS in Section 6. Finally, Section 7 presents a brief summary of the paper.

2 HISTORY OF THE HYBRID SIMULATION TRACK (NM)

The archives of the Winter Simulation Conference (WSC), maintained by the INFORMS Simulation Society (I-SIM, 2024), lists the proceedings of the WSC conference based on the program track. The archival source features HS as a full conference track from WSC 2014. That year, the conference was held in Savannah, Georgia. Although the information is factual, this misses out on some of the earlier thematic sessions that ultimately culminated in creating the HS track. This 10-year anniversary paper is an opportunity to reflect on some of these early start-up efforts. Writing the history has also meant undertaking a mini-information retrieval exercise to find documents that have long been archived.

The first steps towards developing the HS track can be traced back to the WSC 2012 conference in Berlin. Navonil Mustafee, Tillal Eldabi and Simon J. E. Taylor proposed a thematic session that included papers that presented novel ways of combining Operations Research (OR) techniques with computer simulation. The proposal recognized the need for a special session to bring forth research on combining Soft/Hard OR approaches, including qualitative approaches such as Soft Systems Methodology (Soft OR) and deterministic formulations using analytical/mathematical modeling (Hard OR), with stochastic simulation methods. The proposal was a three-page document and solicited papers on methodology (e.g., frameworks for the integration of multiple OR/Simulation techniques), practitioner papers (e.g., OR/Simulation practices with case studies that have applied combined approach to problem-solving) and articles focusing on technology (e.g., integration technologies that enable automation of using integrated simulation/Hard OR approaches). The original proposal was thus academically grounded in hybrid modeling, a term which is being increasingly used to refer to studies combining simulation techniques with cross-disciplinary research approaches from fields of study that extend beyond our core M&S discipline (Mustafee and Powell 2018; Tolk et al. 2021). Our thematic session was part of the main ‘Applications in Healthcare’ track, which was coordinated by Terry Young. Three papers were accepted. The papers *“Mixing other Methods with Simulation is No Big Deal”* (Pidd 2012) and *“Hybrid Simulation for Modelling Large Systems: An Example of Integrated Care Model”* (Zulkepi et al. 2012). The paper by Zulkepi is particularly well-cited with over 85 references (Google Scholar; May 2024). However, the papers were not on hybrid modeling (mixing simulation with the broader plethora of OR methods), but rather HS.

The following year (WSC 2013, Washington, D.C.), Mustafee and Eldabi developed the second proposal for a thematic session on hybrid modeling, but this time the focus was broadened to include HS. The session was called “Application of Hybrid/Combined Simulation Techniques” and was submitted to the track ‘Simulation for Decision Making’, organized by Young-Jun Son and Enver Yucesan. The proposal included a review of abstracts submitted to the WSC 2012 conference, which supported the need for a special track. The review identified eleven abstracts/posters presented at the 2012 PhD colloquium that included references to the use of multiple simulation techniques; this was indicative of future research trends. Further, seven abstracts/posters had titles that included keywords like hybrid, combining, integrating, etc. In the proposal, we identified some of the mixed approaches used by authors in relation to hybrid modeling (e.g., DES + linear programming; ABS + time-series analysis) and HS (DES + SD; Monte Carlo + DES). An additional analysis was based on a quick review of papers submitted to the previous year's track on “Applications in Healthcare”; the choice of the track was based on the time available to write the proposal for a thematic session and the research interests of both the proposers of the mini-track. The analysis again identified papers on both hybrid modeling (two papers that used simulation with integer programming and simulation with balanced scorecard, respectively) and HS (a total of three papers that included the combined application of SD+DES, SD+ABS and SD+DES+ABS, respectively). Our proposal was accepted, and three papers were presented at the thematic session. Two of these papers were on HS and are well-cited. The paper by Djanatliev and German (2013) on *“Prospective Healthcare Decision-Making by Combined System Dynamics, Discrete-Event and Agent-Based Simulation”* has close to 100 citations, and Brailsford et al. (2013) paper on *“Hybrid Simulation for Health and Social Care: The Way Forward, or More Trouble than It's Worth?”* has 40 citations.

These early thematic sessions paved the way for the introduction of the HS track at WSC 2014. We proposed the track with Sally Brailsford, and through discussion and guided by previous submission numbers on papers on the hybrid modelling/mixing methods topic, we decided that for the WSC conference, having a targeted track on HS would ensure the volume of submissions needed to justify a full track; however, papers on hybrid modeling would also be welcomed. The first international technical program committee (TPC) for the track included 22 members. There were many firsts! However, if one has to pick a key performance indicator for success, we would note that our new HS track competed for attention from more general but longstanding tracks such as modeling methodology, and yet the volume of submissions exceeded our expectations, and which contributed to 17 papers being accepted in the very first year as a full conference track! However, in the frenzy of activities on the start-up of the track and the fact that the track organizers did not have the opportunity to mirror earlier editions of the conference or could benefit from track handovers (as is the practice with WSC), meant that we missed the opportunity for a panel paper in the first year. On the positive side, we benefited enormously from the contributions of the UK simulation network; more than half of the WSC 2013 TPC members were from UK institutions; all six tracks were chaired by UK academics. One reason for this was that our international engagement in HS research was in a formative state. Also, as all three track chairs were from the UK, we reached out to the UK OR Society's (ORS) SIG Simulation network and to the regular contributors to the biennial ORS Simulation Workshops (SW).

The track start-up co-ordinators (Mustafee, Eldabi and Brailsford) continued to organize the HS track for the next three years (WSC 2015-2017). In WSC 2015, the TPC included more than 40 members. WSC 2016 saw the highest number of papers being accepted (25 papers)! From 2015 onwards, we introduced panels, which have accumulated good citation counts over the years. The panels were comprised of academics from the US, Germany, and the UK, which also evidenced our outreach to the international M&S community. Table 1 lists the HS thematic and full tracks (the latter identified in grey background).

The panels were a journey of critique and defined future research directions. The three panels organized during 2015-2017 were as follows (citation count is from Google Scholar; May 2024): *"Hybrid Simulation Studies and Hybrid Simulation Systems: Definitions, Challenges, and Benefits"* (Mustafee et al. 2015; 49 citations), *"Hybrid Simulation: Historical Lessons, Present Challenges, and Futures"* (Eldabi et al. 2016; 75 citations) and *"Purpose and Benefits of Hybrid Simulation: Contributing to the Convergence of Its Definition"* (Mustafee et al. 2017; 78 citations). The 2016 panel was particularly provocative, and it made us rethink definitions of HS, for example, could simulations running on analogue and continuous systems be classified as HS? This led to the development of a classification scheme for hybrid M&S (Mustafee and Powell, 2018). A further contribution that owes its genesis to the efforts of the original track co-coordinators to bring forth the advances in HS is a literature review paper on *"Hybrid Simulation Modelling in Operational Research: A State-of-the-art Review"*, published in the European Journal of Operational Research (Brailsford et al. 2019; 400 citations).

WSC 2017 was the 50th Anniversary of the conference, and having HS as a track in this milestone WSC event felt like a good achievement. By this time, the hybrid track was four years old, and if we were to consider the two thematic tracks from 2012 and 2013, it would have been six years!

In 2018, we started discussing the continuity of track organization. This would also allow academics with active research interests in HS to lead the track, benefit from the existing network of peer reviewers, and who would take forward new initiatives. We decided that rotation of track chairs would be a good approach; thus, a new track co-ordinator would replace an existing member. Brailsford stepped down as a co-ordinator after WSC 2017 (having served for four years). For the 2018 conference in Gothenburg (Sweden), Anatoli Djanatliev from the University of Erlangen-Nuremberg, Germany, joined as a track chair. The following year (WSC 2019, Maryland), Mustafee stepped down from track organization responsibility (having served a total of seven years, including leading the thematic sessions), and the team now comprised Eldabi and two new members (David Bell and Antuela Tako). One high point of the 2019 conference was two panel papers, each led by a co-track organizer – *"Toward Conceptual Modeling for Hybrid Simulation: Setting the Scene"* (Tako et al. 2019) and *"Hybrid Simulation Development–Is It Just Analytics?"* (Bell et al. 2019). Following WSC 2019, Eldabi stepped down, and Bell and Tako took leadership of the track for the WSC 2020 virtual conference.

As a concluding note, the HS track has carved an identity amongst other longstanding and popular tracks such as modeling methodology, analysis methodology, simulation optimization, healthcare applications and manufacturing applications. The track was amongst the largest of the WSC tracks in 2016 (Arlington, VA) and 2018 (Gothenburg, Sweden), with 25 and 22 papers being accepted, respectively. After a drop in paper submissions during and subsequent to the COVID pandemic, the numbers are now on the

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Table 1: 10-year History of the WSC HS Track

WSC Year	WSC Location	Thematic Session or Full Track	Track Chairs	Panel Papers
2012	Berlin, Germany	Thematic Session on Combined OR/Simulation Techniques	Nav Mustafee, Tillal Eldabi and Simon J. E. Taylor	
2013	Washington, D.C.	Thematic Session on Application of Hybrid/Combined Simulation Techniques	Nav Mustafee and Tillal Eldabi	
2014	Savannah, Georgia	Full Track (17 papers and six sessions)	Nav Mustafee, Tillal Eldabi and Sally Brailsford	
2015	Huntington Beach, CA	Full Track (15 papers and six sessions)	Nav Mustafee, Tillal Eldabi and Sally Brailsford	• Hybrid Simulation Studies and Hybrid Simulation Systems: Definitions, Challenges, and Benefits (Mustafee et al. 2015)
2016	Arlington, VA	Full Track (25 papers and nine sessions)	Nav Mustafee, Tillal Eldabi and Sally Brailsford	• Hybrid Simulation: Historical Lessons, Present Challenges, and Futures (Eldabi et al. 2016)
2017	Las Vegas, NV (50th Anniversary of WSC)	Full Track (16 papers and six sessions)	Nav Mustafee, Tillal Eldabi and Sally Brailsford	• Purpose and Benefits of Hybrid Simulation: Contributing to the Convergence of Its Definition (Mustafee et al. 2017)
2018	Gothenburg, Sweden	Full Track (22 papers and eight sessions)	Nav Mustafee, Tillal Eldabi and Anatoli Djanatliev	• Hybrid Simulation Challenges and Opportunities: A Life-Cycle Approach (Eldabi et al. 2018)
2019	National Harbor, Maryland	Full Track (17 papers and seven session)	Tillal Eldabi, David Bell, and Antuela Tako	• Toward Conceptual modeling for hybrid simulation: Setting the Scene (Tako et al. 2019) • Hybrid Simulation Development – Is It Just Analytics? (Bell et al. 2019)
2020	Virtual Conference	Full Track (8 papers and three sessions)	David Bell and Antuela Tako	
2021	Phoenix, AZ (hybrid conference)	Full Track (4 papers and two sessions)	David Bell, Caroline C. Krejci and Antuela Tako	
2022	Singapore	Full Track (10 papers and four sessions)	Andrew J. Collins, Caroline C. Krejci and Antuela Tako	
2023	San Antonio, TX	Full Track (14 papers and five sessions)	Anastasia Anagnostou and Antuela Tako	

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of the track is one of the first history papers reflecting on the HS track!

3 NATURE OF HYBRID SIMULATION APPLICATIONS (TE)

As mentioned earlier, HS is the use of two or more simulation methods, typically combining the three main methods, that is, DES, SD, and ABS. The hybridization process may include other forms of modeling, other than Simulation, this is defined as Hybrid Modeling (HM) (or Hybrid Analytics). Since its inception 10 years ago,147 papers have been published within the HS track at the WSC. The pattern of publications included HS, HM, and simulation with other forms of modeling. These papers exhibited various techniques and application areas. In this section, we will present general reflections on the last decade in terms of the types of techniques used and sectors.

3.1 Applied vs. Theoretical

Out of the 147 papers, 56% of papers are applied, i.e., looking at real-life problems, while 44% of the papers are of theoretical nature. Many of the applied papers did not show clear evidence of implementation, however, the data show that most HS models tend to be more practical than theoretical. This is explained in Brailsford et al. (2019) that HS is usually resorted to after the commencement of the solution process rather than as a theoretical idea or during the conceptual phase.

3.2 Hybrid Techniques

The most interesting aspect of this section is that 55% of the studies used HM rather than HS. While the main focus of the track is HS, other types of modeling approaches were included as part of the overall hybridization concept. Another interesting finding is despite the apparent dominance of DES/SD hybrid models, Table 2 shows a significant prevalence of ABS, either in dual or triple hybridization. Moreover, although the triple hybridization (ABS–DES–SD) is normally known to be used less compared to dual hybridization, it is shown to be much higher in WSC. The caveat to that is that the triple approach is mainly developed in conjunction with methodological or theoretical papers rather than applied papers. The most

Table 2: Analysis of the HS Techniques

Technique	No.	%
Hybrid Modeling (other than Simulation)	55	37%
ABS/DES/SD (Triple HS)	33	22%
ABS/DES	24	16%
VOID	6	4%
AI Hybrid Modeling (AI and other models)	7	5%
ABS/SD	5	3%
DES Hybrid Analytics (DES and other models)	5	3%
DES/SD	4	3%
ABS Hybrid Analytics (ABS and other models)	2	1%
SD Hybrid Analytics (SD and other models)	2	1%
CPS (Cyber Physical System	1	1%
AI/DES	1	1%
AI/ABS	1	1%
AI/SD	1	1%

important fact in the table below is the popularity of ABS. A rising trend that will increase in the future is Artificial Intelligence (AI) related techniques. AI is predicted to play a major role in the advancement of HS.

3.3 HS Application Area

Thirty-nine out of the 147 papers were solely focusing on methodological approaches of HS with no specific application area. This is understandable given the novelty of HS. In terms of application areas (sectors), we found that healthcare papers represent 29% of all sectors, which matches most HS reviews. In fact, the first three categories (out of 20 categories) have 52% of the papers (see Table 3). These are usually complex systems stressing the usefulness of HS for modeling such systems. What is interesting is the emerging trend of the use of HS for modeling human behaviors and related behavioral aspects. Probably because most of the complex systems tend to involve more humans within their processes. With the advancement of technology, HS will be used more for modeling the behavioral aspects of the system.

In summary, while some of the trends exhibited here match those of previous major reviews, it was quite an eye-opener to see how some of the trends are quite different from known assumptions. For example, the prevalence of ABS in hybrid format compared to DES. Another important lesson is HS and HM are seen as vital ways of thinking when tackling complex situations. Finally, the healthcare sector seems to be the most important use area for HS and will continue to rise.

Table 3: Analysis of the HS Application Areas

Application Area/Sector	No.	%
Methodology	39	
Healthcare	31	29%
Behavioral (Huma Elements)	13	12%
Logistics	12	11%
Environmental	6	6%
Panel discussion	6	6%
UAV	5	5%
Manufacturing	5	5%
Workforce Planning	5	5%
Review	5	5%
Software	3	3%
Production	3	3%
Science	3	3%
Urban	3	3%
COVID19	2	2%
General Planning	1	1%
Construction	1	1%
Conflicts and Security	1	1%
Sports	1	1%
Space	1	1%
Service	1	1%

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4 MODELING TOOLS AND SOFTWARE (AA)

Arguably, conducting an HS study is more challenging than conducting an M&S study using a single simulation technique. As highlighted in Mustafee and Powell (2018), the use of multiple techniques is not necessarily restricted to coding or developing the computer simulation. In a comprehensive multi-paradigm study, multiple modeling techniques are applied to all of the stages of a simulation study. The term, coined to describe the use of combined multiple approaches for conceptualization, input/output analysis, verification & validation, as well as experimentation, is Hybrid Systems Modelling (HSM). Examining the papers published in the HS track over the last decade, one could argue that the majority of the studies perform HSM. That is, the applications, and even the theoretical developments, do not only combine SD, DES and ABS but they utilize multidisciplinary methods to express the stages of an HS study. Here, we look at some examples and discuss relevant technologies, challenges and considerations of each stage following the phases of the proposed framework for hybrid model development by Eldabi et al. (2019).

The *conceptual phase (Phase 1)* includes three steps, reflecting the problem formulation, the conceptual modeling and modularization process of the hybrid model, and the identification of the characteristics of each module.

The first step of formulating the problem aims at establishing the need for HS, and in fact whether simulation is needed at all. Observing the published papers in the HS track in the last decade, the main justifications for employing HS are: (i) The complexity and heterogeneity of the system. For example, does the analysis require explicit interaction of objects, that could be modeled as agents in ABS, or just to distinguish individual objects, that could be developed as entities in a DES model? (ii) The scale of the system. This can refer to the timescale or the size of a system. For example, is there a need to combine longer and shorter-term analysis? A typical approach in this case is to employ SD with a combination of DES or ABS. (iii) The modularity of the system. For example, whether the system elements have clear boundaries and can be modeled as distinguished components/modules with defined boundaries and interfaces. In this case, a benefit of choosing HS is claimed to be the reusability of the individual modules.

The conceptual modeling and modularization of the process is the second step. There are considerable efforts in developing conceptual modeling approaches for HS. For example, Powell and Mustafee (2014) discuss the use of soft OR approaches for problem formulation, Zulkepli and Eldabi (2015) introduce a framework for HS conceptual modeling in healthcare, and Jones et al. (2022) present a method for general representation of an HS study. However, as noted in Tako et al. (2019), currently there is no specific conceptual modelling approach available to support HS in general. Nonetheless, there are some notable examples in specific application areas. Onggo (2014) presents a conceptual model for a hybrid SD and DES model in blood supply chain, where the author uses conventional conceptual representations of the individual models, that is stock and flow diagram for the SD model and business process modeling notation (BPMN) for the DES models. The interface of the modules is rather descriptive, nonetheless there is a comprehensive analysis of the synchronization between the modules. Saleh et al. (2021) use ontologies to conceptualize DES processes that utilizes disease spread predictions from an ABS model. Reitz et al. (2022) discuss a conceptual framework for HS using a co-simulation approach.

The identification of the characteristics and requirements for each module is the third step. Here modelers decide the appropriate simulation techniques based on the type of analysis, as well as define the modules. For this step, most of the published studies use the conventional conceptualization methods of each individual technique. Typically, stock and flow and causal loop diagrams are used to represent an SD system, use case and activity diagrams are widely used for ABS and flow charts and BPMN diagrams are used to conceptualize DES processes. Apart from the design tools of most of the simulation packages, there are several tools available to support the development of such diagrams. Some examples are Visual Paradigm (https://www.visual-paradigm.com), MS Visio (https://www.microsoft.com), draw.io (https://www.drawio.com).

Nonetheless, as noted in Tako et al. (2019), more inclusive approaches are need to broaden participation in HS modeling. Such approaches could be basic modeling forms such as natural language and basic

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drawing, as well as well structure methods to elicit knowledge from stakeholders such as the PartiSim framework for facilitated simulation (Tako and Kotiadis 2015; Kotiadis et al. 2014).

The *modeling phase (Phase 2)* deals with the actual coding of the individual models with special considerations for the identified data and time synchronization aspects. The individual models are developed/coded using either a commercial-off-the-shelf (COTS) simulation package, such as Stella (https://www.iseesystems.com), Vensim (https://vensim.com), Simul8 (https://www.simul8.com), Anylogic (https://www.anylogic.com), Arena (https://www.rockwellautomation.com), etc. or coded from scratch using a high-level programming language such as C++, JAVA, Python, etc. There are also many free and open-source simulation frameworks, such as Simantics (http://sysdyn.simantics.org), SimPy (https://simpy.readthedocs.io), Salabim (https://www.salabim.org), the Repast Suite (https://repast.github.io), NetLogo (https://ccl.northwestern.edu/netlogo), the GAMA Platform (https://gama-platform.org), MASON (https://cs.gmu.edu/~eclab/projects/mason), etc., that provide structural simulation components, such as implementation of schedulers, queues, topologies, etc. These frameworks support the development effort, however considerable amount of coding is still required.

Observing the papers in the WSC HS track, the majority of the works that report implementation is developed in Anylogic, which, at the time of writing, is the only COTS that supports all the three main simulation paradigms. Also, because these models are developed on a single simulation package, it is simpler to implement the links between the models. Sometimes, as noted in Brailsford et al. (2019), it is hard, or even impossible, to distinguish the boundaries of the simulation methods. There are other examples, however, that use different tools to develop the individual models. Stella and Simul8 is used by Bell et al. (2016) for their hybrid SD and DES model of non-elective health provision. Lather and Eldabi (2020) present an example of hybrid SD and DES for COVID-19 combining a SEIR infection model with ICU bed management using Vensim and Simul8. Interestingly, the authors use the online version of the models and discuss the benefits of reusability. Python is used by Anagnostou et al. (2022) to model COVID-19 spread at regional level and ICU bed management in an ABS and DES hybrid model. They developed the ABS from scratch and the DES using the SimPy libraries. A combination of Python and Java in Anylogic is used by Moallemi et al. (2018) for a hybrid multi-objective simulation optimization model for fleet management. The authors used the open-source Exploratory Modelling Workbench, which is in Python, for performing computational experiments and implementing multi-objective optimization, and Anylogic, which is Java-based, to model their SD and DES fleet management model. Gütlein and Djanatliev (2019) present a multi-level traffic HS developed in C++. Their model is developed as distributed simulation (Taylor 2019) and uses High-Level Architecture (HLA) for data and time synchronization. An interesting hybrid approach is reported Ruiz-Martin et al. (2016), where the authors use a combination of ABM, Discrete Event System Specification (DEVS), network theory and Monte Carlo Simulation to model communication as information transmission in emergency situations.

The *models communication phase (Phase 3)* includes four steps, dealing with identifying the linking variables, identifying the interaction type, executing the model and exchanging data, and evaluating the outputs.

One could argue that the rationale of the first two steps is defined in the conceptualization phase. Nonetheless, the implementation of the communication means and linkage of the models falls in this third phase. When the HS is implemented in a single package, modelers need to define the connections but the software deals with the actual interactions. This is the case when the HS is developed in Anylogic, for example. However, there are many studies that implement the data exchange as middleware or file sharing interface. For example, Blasch (2018) use HLA to exchange data in a Dynamic Data Driven Applications Systems (DDDAS) HS. Strassburger (2015) presents an HLA optimistic synchronization approach for HS, built in the Simulation Language with Extensibility (SLX) DES language developed by the Wolverine Software Corporation, aiming at speeding up the simulation execution. Viana (2014) discuss the use of MS Excel as an interface between Vensim and Simul8 that facilitates data exchange. Finally, Mustafee et al. (2022) present two examples of interfacing Simul8 with forecasting models using Visual Logic, its built-in programming language, and HLA for distributed HS.

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The latter, as well as the HS models of Blasch (2018) and Strassburger (2015) are example of a distributed simulations, where the individual models of the HS are executing on different computing nodes. Typically, HS models built on a single COTS run on a single computer. Lately, however, most of the COTS provide online versions of the software where simulations can be executed on cloud environments. HS models that are built as distributed and/or parallel simulations are run on distributed computing infrastructures, such as grids, clouds, or supercomputers. A trend that we have seen in recent years is to develop HS systems as microservices (Blasch et al. 2019) but this approach is not yet widely adopted. In this case, the data exchange between the models is implemented as a message queue and the whole HS system constitutes a pipeline of services. This approach can be particularly convenient when many peripheral components are involved, as in the case of digital twins.

The last step of this phase is the evaluation of outputs, which are the produced KPI values that are used to analyze the results and present them to the decision-makers. An important activity of this step is to define the experimentation strategy and decide what scenarios are to be evaluated.

As for conceptual modeling, there is no specific approach for verification and validation (V&V) for HS. This is noted in Eldabi et al. (2018) as well, where the challenges of validating HS models are discussed. The authors, in the concluding remarks, make the following observations with regard to HS V&V: (i) Intra-modular VV methods are similar to single models; (ii) Inter-modular VV methods add extra dimensions to validation; and (iii) Non-uniformity of testing methods require more effort and skills.

Arguably, the choice of the tools for representing the conceptual model, the software for the models development and their communication implementation is influenced by the modelers' background and expertise. A quick observation, for example, indicates that modelers with OR background use mostly COTS software packages while the ones with computer science background prefer to use open-source frameworks or code the model from scratch. In all cases, however, conducting HS studies is more complicated, time-consuming and requires expertise in multiple modeling paradigms. This is not restricted solely to programming skills, it extends to the whole philosophical view of the system and the questions that need to be answered by the simulation experiments.

To conclude, although there is a lot of progress in HS technologies, the implementation of an HS project still presents significant challenges. Nonetheless, the benefits of combining simulation techniques are clear, especially when modeling complex heterogeneous systems.

5 IMPLEMENTATION AND USER PERSPECTIVE (AT)

As noted in Section 3, more than half (56%) of HS papers published in the HS track are of an applied nature, which suggests that a good proportion of these studies are based on real-life problems. This section considers the extent to which model results and/or findings are implemented and how the user perspective is embedded in the studies presented in the track over the last decade. After a closer examination, a few observations can be made.

A first observation is that despite the fact that the majority of papers published in the track over the 10-year period are on an applied topic, there is limited discussion about the implementation of the model findings or results. This is not to be confused with the implementation of the model code. For clarity, we consider here any references made in the paper related to how the model has been (or will be) used to inform decision-making in the real world, part of the *Model communication phase* of the HS framework proposed by Eldabi et al. (2019). Instead, the papers often focus on the technical aspects of hybrid modeling, considering the underpinning methodology that guides the development of modules or the interconnecting interface between the modules. This is not surprising considering that HS is in its infancy. Furthermore, it is noted that conference papers often tend to present preliminary models or 'work in progress', meaning that the models have not yet reached the implementation stage at the time of publication.

A significant number of HS models presented in the track (29%) are applied in the healthcare sector. Healthcare provides many practical examples for the application of HS models, evidenced also by two literature review papers being published on this very topic in the HS track! Due to the complex and interconnected nature of health systems and their problems, one simulation approach may not be sufficient

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to represent an optimal view of the different parts of the system, which explains why HS in health is very popular. Indeed, the review by Santos et al. (2020) found just 12 relevant papers, whereas only two years later the review by Kar et al. (2022) found 33 papers out of which 24 were considered suitable for inclusion in the analysis, this is in fact double the number of papers found in the Santos et al. (2020) review.

Another observation made by Kar et al. (2022) in their review was that most HS models are problem-specific, which can be counterintuitive considering that a lot of time and effort is spent to develop these models. To make better use of these models the authors suggest model re-use, whereby models could be shared in open-source platforms such as GitHub for other modelers to use and/or link with other models. However, for this to be possible a need for an overarching generic problem-agnostic framework is needed so that modelers can map their models or modules against specific components and criteria.

Additionally, it is noted that validation of HS models published in the track is limited. More often than not, details regarding model validation and verification for hybrid models tend to be limited, with these activities focused on the individual sub-models and not the overall model. For example, in their review Kar et al. (2022) found that out of 24 papers included, only 41% of the application papers used statistical results, 20% used face validity and statistical methods and only one used external validation, while the rest did not consider any verification and validation activities. More robust validation is needed and especially validation against real life data as well as through involving model users to ensure that the models developed are fit for purpose and representative of the real-world systems. This is identified as an area for future development for HS as it is important that model users and the public build trust in the models developed and their results.

Now looking more closely at user involvement, it is also noted that very few papers discuss involvement of decision-makers or model users in the modeling process. The level of involvement varies amongst papers, with some papers referring to the ultimate aim of developing models to be used by decision-makers, however the input of decision-makers or model users is often limited. For example, Endrerud et al. (2014) present a hybrid model of marine logistics and comment that the model is being developed in collaboration with project partners as part of a funded project. Even though the model presented is work in progress, the authors comment about their intention to develop a model that can be used as a decision support tool by domain experts. Anagnostou et al. (2022) also develop a hybrid agent-based and DES for the Coronavirus pandemic management, which aims to predict the impact of public health prevention measures at regional level. While no details of engagement with stakeholders are provided in the paper, the models include a user interface for users to input their data and use the models, which are made publicly available. Similarly, Moallemi et al. (2018) present a multi-objective model of the acquisition problem of a fleet of submarines and note that decision-makers can interact with the tool developed to choose the best solution.

The input of stakeholders into the modeling can take, for example, the form of real-life data collection in the chosen case study application area as future activities for the project (Mittal and Krejci 2015). Model co-design with stakeholders does not occur often. Only one paper has discussed co-design (Gholami and Sarjoughian 2016). The authors consider simulation model co-design within the wider software and hardware co-design paradigm of a complex network software system called Network-on-Chips. In another paper, Lei et al. (2023) present an Information and Communication Technology (ICT) manufacturing supply chain (SC) model, which incorporates domain expert knowledge into the model via Delphi elicitation. This involves obtaining expert feedback to reach a consensus or expert judgment to overcome issues with data confidentiality.

In the early years of the track Powell and Mustafee (2014) suggest the use of soft OR approaches for the initial stages of problem understanding. Later on, a tutorial paper presented in WSC 2019 on means of HS considered aspects related to HS modeling and design (Eldabi et al. 2019) and it discusses, among others, the potential and benefits of using facilitation as a means to including stakeholder input to the HS modeling process. Facilitation can help to capture the diversity of opinions about the problem situation, the model and its results amongst stakeholders with a vested interest in the model and/or potential model users and to ultimately reach a common understanding between all those involved. A panel paper on conceptual modeling for HS also recommends the use of facilitated modeling to design the conceptual models (Tako

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et al. 2019). Facilitated simulation is the process whereby a group of stakeholders (modelers and clients) work jointly to co-develop simulation models, to reach consensus about the subjective views of the problems represented in the models and the anticipated solutions (Tako and Kotiadis 2015; Kotiadis and Tako 2018). Through this process stakeholders provide their inputs in model co-creation workshops contributing towards the final model and results. It also ensures that the process and the resulting outputs are transparent to the group of stakeholders involved. At the time, stakeholder engagement had received little attention in the HS track. The panel made a call to action for modelers to consider embedding facilitation and using facilitation tools such as PartiSim when building HS models.

Against this backdrop, a review by Santos et al. (2020) published just one year later found limited use of soft OR techniques to support the problem formulation stage, as a complementary method for developing hybrid models. After reviewing more closely the papers published in the track over the 10-year period, it is noted that stakeholder engagement continues to be limited, at least based on the papers included in the track, very few authors tend to co-create their models involving model users or clients. The exception is a study by Jones et al. (2019) who explain their stakeholder engagement in developing hybrid models with two different groups of stakeholders in the transport industry for Eurostar International Limited. The authors show how they identify further uses of a HS model by engaging with stakeholders beyond its first lifecycle to extend its use and benefits. The authors claim that by undertaking a second loop of the modeling process can offer further details and improve the operational effectiveness of the simulation models.

Based on the above, we can conclude that even though HS models aim to be applied and problem-focused they are often built with limited stakeholder involvement. This is not surprising given that the field is still in its infancy. Existing frameworks such as PartiSim can be used to support modelers or even consider developing frameworks that are tailored to HS modelling. It is clear that model re-use, stakeholder engagement and facilitation are areas of further development for the HS community that we hope will appear in future HS tracks.

6 THE FUTURE OF HYBRID SIMULATION (SB)

Based on its rapid growth in popularity in recent years, HS is not only here to stay but its use will continue to expand since it is now taught in many universities alongside traditional, single-method approaches. As a result, a new generation of young simulation professionals will enter the world of work with all the necessary skills to use HS in practice, mirroring the way in which the DES software Simul8 (https://www.simul8.com), initially developed solely for teaching purposes, found its way into the commercial world and is now a top player in the global market. However, the fact remains that there is still essentially only one off-the-shelf hybrid software tool available for general purpose modeling, as opposed to domain-specific software for engineering applications. This is of course AnyLogic, (https://www.anylogic.com), and while the free Personal Learning Edition is ideal for educational purposes it cannot be used commercially or for published academic research. Open-source tools without these drawbacks are obviously also available, but not only do these require programming skills, they lack the high-quality graphics produced by commercial software that is essential when communicating with stakeholders. This lack of market competition is surprising, despite the efforts of vendors to augment established single-method software tools by including features of other approaches: for example, the SD software Stella Architect now incorporates elements of DES such as queues and discrete batches. However, such tools still essentially retain the ‘DNA’ of their original approach, and the additional method is simply a bolt-on; it would not make sense to try to build a pure DES model in Stella Architect, for example.

Fourteen years ago, in a lively panel discussion entitled ‘DES is dead, long live ABS!’ at the *2010 UK Simulation Workshop* (Siebers et al. 2010), I argued that ABS would never be widely adopted until it had an equivalent of Simul8: in other words, a user-friendly tool with a drag and drop user interface, suitable for teaching Business School students who cannot (or do not want to learn how to) write computer code. The developers of Simul8 accepted this challenge and added statecharts to an experimental version of their software; this capability was subsequently included in the commercial version, although it is not as flexible as AnyLogic and does not reflect the full range of ABS functionality (Penny et al. 2022). AnyLogic remains unique in its ability to combine all three simulation methods and without doubt has become far more user-friendly, flexible, and powerful over the past decade. Whereas in the past an experienced DES modeler, say, would almost certainly have chosen to use a bespoke DES tool rather than AnyLogic (Brailsford et al. 2013), this may well not be the case today. Nevertheless, it still feels odd that AnyLogic, which has been around for nearly 25 years, continues to have a monopoly in the HS software market. My first prediction is therefore that in future, genuine commercial challengers to AnyLogic will appear; moreover, these will not be extensions of existing single-method tools but will be entirely new.

My second prediction is somewhat less contentious, namely that as the popularity of HS increases, its areas of application will expand and diversify. Five years ago, Brailsford et al. (2019) found that the three main application domains were healthcare (22%), supply chain logistics (19%) and manufacturing (17%), with no other domain exceeding 9%; the authors argue that this reflects the research interests of the relatively small number of early adopters of HS, as well as the nature of problems arising in these areas. Over the next decade these three areas will continue to be popular, but they will not dominate as they did in the past. Environmental issues, sustainability and climate change, for example, are likely to see rapid relative growth in coming years.

Brailsford et al. (2019) identified a number of areas where further methodological research is required; for example, developing diagrammatic methods for conceptual modeling, and methods for verification and validation, specifically for hybrid models. Academics are already making good progress on these, for example, Tolk et al. (2020), Farhan et al. (2021) and Jones et al. (2022), but in coming years I predict that simulation academics will continue to find HS a fertile area for new theoretical research.

My fourth and final comment is more philosophical. Andrei Borshchev, the founder and CEO of AnyLogic, once said that in future, people would no longer say 'a DES (or SD, or ABS) model' but would simply say 'a simulation model'. In other words, the boundaries between the three methods would become so blurred that people would forget they were originally distinct approaches with their own world views, research communities, jargon, and journals. While (up to a point) I agree with this statement, especially as a new generation of hybrid modelers is gradually replacing the 'old timers' who only ever learned one method, I still believe that 'SD modelers and DES modelers just see the world in a different way; this affects the way they conceptualize and model problems, which is far more subtle than merely the distinction between discrete and continuous variables' (Brailsford et al. 2010). The 'holy grail' of true integration of these two philosophies is a lot more challenging than merely including stocks and flows in a DES model, or queues in an SD model, and is in my view unlikely ever to be fully achieved.

7 SUMMARY

The paper presented opportunities and challenges of HS as these are observed in the proceedings of the 10-year presence of the WSC HS track. It provided a historical view starting from the idea inception as a means to provide a venue for the growing area of HS. A review of the published work was presented from three different perspectives: (i) the nature of the HS applications focusing on the combined techniques and application area, (ii) the technological advancements in terms of modeling tools and software for HS, and (iii) the implementation and user perspective focusing on stakeholder involvement in HS project development and to what extend facilitative and co-design approaches supporting increase of trust and confidence in the model and the experimental results. Finally, the paper presents a vision for the future of HS reflecting on four aspects: (i) new software for HS, (ii) expansion and diversification of application areas, (iii) methodological and theoretical growth, and (iv) philosophical worldview about the boundaries of the HS components.

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