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# THE BENEFITS OF A HYBRID SIMULATION HUB TO DEAL WITH PANDEMICS

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## ABSTRACT

The advent of COVID-19 has shaken the whole world to its core. With many decision makers at all levels trying to tackle the spread of the disease and the economic ramification, the modeling and simulation is of paramount importance as part of this effort. Given the intricacy and interconnectedness of the problem, hybrid simulation (HS) seems to provide better support for modelers given its ability to connect multiple decision categories. However, HS models are known to take longer to build while requiring multiple expertise, which does not match the rapid impacts of COVID-19. To allow for faster means for developing such models, in this paper, we call for the establishment of a hub for rapid HS model development through global collaboration of simulation modelers. In the lack of such hubs, we demonstrate how a HS model could be built using publicly available single-method models.

## 1 INTRODUCTION

Pandemics are known to occur since the beginning of time. Over centuries pandemics killed millions of people at any one time. The Black Death pandemic, which took place in the 14th century, recorded by far the highest rate of deaths with approximately 200 million people losing their lives between 1,347 and 1,351 (DeWitte 2014). The rapid advancement of medical knowledge and technology helped the eradication (and/or drastically reducing the impact) of pandemics. Such advancement is supported by better hygiene, availability of vaccines and overall community better awareness of healthy lifestyles. This culminated in significant successes in the last 50 years against many pandemics. However, the recent rise of COVID-19 virus opened the lid on some further dimensions that were not exposed before. That is, and although the spread of the disease can be predicted with great accuracy, there exist a number of factors that allowed for the unprecedented expansion of the virus and the total disruption that came with it. The first dimension is that the interconnectedness of metropolitan areas and the expansion of high-rise buildings coupled with congested public transport networks, created large areas of crowded places leading to faster contagion despite cleaner environments in cities. Secondly, travelling between cities and beyond national borders, thanks to the abundance of affordable air travels, allowed for the speedy international spread of the disease. Thirdly, and quite ironically, the accumulation of knowledge and tools to tackle pandemics such as isolation and lock-downs, created huge economic challenges. Therefore, the advent of COVID-19 led to an unprecedented competition of decisions between saving overwhelmed healthcare systems and energizing a paralyzed economic productivity within a widely interconnected context. This in turns gave rise to the immediate role of modeling and simulation in supporting such decisions more than ever. There are many articles that show the benefits of modeling during pandemic (Ferguson et al. 2005; Epstein 2009; Bosch 2019; Currie et al. 2020). Whilst earlier research focuses on directly predicting the spread of the epidemic, Currie et al. (2020) alert modelers and decision makers alike to the importance of thinking beyond the pandemic curve. We see that the role of Hybrid Simulation (HS) is even more vital within the realm of modeling pandemic related decisions. The above authors, with particular reference to Currie et al. (2020) where the focus is COVID-19, have mainly opted for dividing the pandemic into a number of categories of decisions (or subsystems) for either managing the pandemic itself or its associated issues, such as logistics, vaccination, testing etc. (Currie et al. 2020). While each category is proposed with specific and relevant modeling approaches, in this paper we aim to highlight the role of HS as a vital facilitator for linking models between the different categories. Our focus here is solely on hybridization between Discrete Event Simulation, System Dynamics, and Agent Based Simulation. With this in mind, the aim of this paper is to show how it is possible to build a viable HS model based on publicly available single-approach models and propose the establishment of a modeling hub where different models from different backgrounds and localities can be used to rapidly develop a stronger modeling response during the pandemic. The following section define what we mean by HS and lays out its uses in the fight against COVID-19. This is followed by an initial proposition of the concept of modeling hubs to support rapid development of HS models during crisis times. In the absence of purpose-built hubs, Section 4 provides a conceptual explanation of how HS models could be built based on publicly available models. This is followed by a demonstrative example before we conclude by providing some lessons learned and a proposed roadmap in this topic.

## 2 HYBRID SIMULATION AND COVID-19

HS is defined as the "application of two or more individual simulation techniques to implementation and model development stage of a simulation study" (Mustafee and Powell 2018). For example, a HS can use several models which can either be embedded in the same model or connected via inputs and outputs of several federated models and sub models. There are three main simulation approaches: Discrete Event Simulation (DES), System Dynamics (SD), and Agent Based Simulation (ABS).

HS is recently rejuvenated due to the rapidly rising complexity of health and social care systems (and the overall service sector). Problems such as congested emergency departments and obesity epidemics are commonplace now more than ever. Examples of how simulation and analytics are used to tackle such complexities have been widely reported (Brailsford et al. 2019). While the above approaches struggle to cope with complex systems in singular forms, HS emerged as a strong candidate to overcome such challenges (Zulkepli and Eldabi 2015). The basic concept of HS to utilize the corresponding characteristics of each of the simulation approaches in a complimentary manner. Despite the potential benefits of HS and the growing interests several challenges are reported to be addressed beforehand (Eldabi et al. 2018). For example, most of the current attempts are ad hoc and based on academic curiosity (Lamé and Simmons 2018); lack of platforms to link models (Brailsford et al. 2019); no clear methodological approach to develop HS conceptual models (Eldabi et al. 2016); and the rising cost of using more than one package (Brailsford et al. 2019). Currie et al. (2020) is the first comprehensive article to highlight the role of modeling and simulation for the fight against COVID-19 from a purely modeling perspective. HS is mainly used as a means to compensate for the disadvantages associated with using single-approach models. For example, developing a personal protective equipment (PPE) supply chain model using DES could be enriched by the output generated from a SD model of lockdown policies rather than depending on randomly generated demand patterns. On the other hand, a SD model for assessing the best policy to end lockdown could benefit from rates of disease spread according to the same policy in another ABS model mimicking people's reactions to such policies. However, in fast-paced and dynamic pandemics the choice of modeling approach is mainly guided by available expertise and licenses, and not by the breadth of possible techniques. Therefore, our intention is to find better ways to build HS models faster and with less reliance on one individual/organization to have extensive expertise in multiple methods.

## 3 OPEN HUBS FOR HYBRID SIMULATION

In this section we will look at how HS can be used in an effective manner to enhance the modeling effort for the fight against COVID-19. As discussed in the previous section, HS helps in enriching single pandemic related models from different categories. Notwithstanding the added benefits of using HS, COVID-19 is a rapidly rising global disaster and requires expedient modeling approaches to tackle it. This may be challenging for HS where modeling effort usually takes longer than single-approach methods, in addition to the rarity of people with multiple methods expertise. In order to overcome this challenge, we envision the development of HS models utilizing already publicly available models. During the rise of COVID-19 many modelers have developed and uploaded their own models based on single method approaches. People are generally encouraged by their urge to support each other by uploading more models and collaborate with others during crisis times. This presents us with an opportunity to utilize these models to build viable HS models to widen the picture. To support this effort, open platforms (modeling hubs) may be needed for both data and models exchanges Currie et al. (2020). Data should include input data, either measured or estimated, and output data of estimated performance metrics and additional data for use in other models (e.g., flow data and capacity data). Models can be categorized into whole models as well as partial models (e.g., ways of modeling certain processes). As the different models are built in different environments and locations, an ideal HS hub should facilitate data transfer automation. At this stage there is no clear strategy of how this can be done, however, one way to do it is to develop open source conceptual models, which could be validated later amongst multiple instances of the same system family (e.g., hospitals and clinics, similar organizational systems). By understanding the variations across multiple systems, these models and model elements would open new avenues for simulation analytics and performance estimation.

## 4 TOWARDS HYBRID SIMULATION HUB FOR COVID-19

Currently there is no specific infrastructure for establishing a hub as proposed above, therefore, in this section we present the building blocks for developing HS models using the current models without the hub. Here we reproduce the set of decisions proposed by Currie et al. (2020) where modeling could be used to support the fight against COVID-19. Online models could be linked with each other to develop a HS model in a much shorter time – compared to models built from scratch. Previous research has developed frameworks for large HSs (Zulkepli and Eldabi 2015), where it is important to (and how to) identify the communications between different models and sub models. Table 1 provides a list of the aforementioned decisions, their corresponding models (Currie et al. 2020). To support using current models to build larger HS models, we present the potential linking variables - i.e. variables that can be received from other models and variables that can be sent to other models. For example, in the first row, the SD model in Decision 1 would receive death rates from the DES model in Decision 6. In turns, the SD model in Decision 1 would send disease progression (number of infected people) to the SD model in Decision 3 and levels of demands for PPE and food to DES model in Decision 8, and so on. Figure 1 provides a visual representation of the links established in Table 1. Figure 1 summarizes the interconnectedness of the different models and the possible variables that can be transferred between sub models. Whilst it is possible to take decisions and develop the models in silos, using HS will enrich the sub models by replacing assumptions with outputs from other models. Hence, the outcome of any of these decisions will be very much enhanced. It must be noted here that the set of decisions discussed here may not be an exhaustive list of the relevant decisions and that the links are not comprehensive where many more combinations could be established.

Table 1: List of COVID-19 related decisions (Currie et al. 2020) and their input and output linking variables with related decisions.

| Decision | Suggested Modeling Methods | Receives variables from: | Sends variables to: | Model(s) available online |
|---|---|---|---|---|
| ***1. Quarantine Strategies, Case Isolation, and Contact Tracking*** | SD for population-level models;<br>ABM for models that capture individual behavior. | ***Decision 6***<br>(Hospital death and survival rates). | ***Decision 3***<br>(Disease progression rates). | Behavioral Infectious Disease Simulator (Struben 2020);<br>The COVID-19 Simulator (ISEE systems 2020);<br>COVID-19 Outbreak and Policies (Castillo 2020a). |
| | | | ***Decision 8***<br>(Demand levels for food and PPE resources and People buying rates). | |
| | | | ***Decisions 6/7***<br>(ICU arrival rates). | |
| | | | ***Decision 11***<br>(rates of people in isolation and shielding). | |
| ***2. Social Distancing Measures*** | SD for population-level models;<br>ABM for models that capture individual behavior;<br>DES or HS for operational models | ***Decision 6***<br>(Hospital death and survival rates). | ***Decision 3***<br>(Disease progression rates). | Behavioral Infectious Disease Simulator (Struben 2020);<br>The COVID-19 Simulator (ISEE systems 2020);<br>COVID-19 with social distancing (Castillo 2020b). |
| | | | ***Decision 8***<br>(Demand levels for food and PPE resources and People buying rates). | |
| | | | ***Decisions 6/7***<br>(ICU arrival rates). | |
| | | | ***Decision 11***<br>(rates of people in lockdown). | |
| ***3. How to Manage the End of Lock Down*** | SD for population-level models;<br>ABM for models that capture individual behavior. | ***Decisions 1/2***<br>(Disease progression rates). | ***Decisions 1/2***<br>(update disease progression to assess impact). | A Community Coronavirus Model for Bozeman (Fiddaman 2020) |
| ***4. Delivery of and Targeting of Testing*** | SD for population-level models;<br>ABM for models that capture individual behavior;<br>DES for delivery of testing. | | ***Decision 8***<br>(Demand levels test equipment and logistics). | Behavioral Infectious Disease Simulator (Struben 2020);<br>The COVID-19 Simulator (ISEE systems 2020). |

Table 1: (cont.) List of COVID-19 related decisions (Currie et al. 2020) and their input and output linking variables with related decisions.

| Decision | Suggested Modeling Methods | Receives variables from: | Sends variables to: | Model(s) available online |
|---|---|---|---|---|
| ***5. Delivery of and Targeting of Vaccination*** | SD for population-level models;<br>ABM for models that capture individual behavior;<br>DES for delivery of vaccination. | | ***Decision 8***<br>(Demand levels vaccination equipment and logistics). | Behavioral Infectious Disease Simulator (Struben 2020);<br>The COVID-19 Simulator (ISEE systems 2020). |
| ***6. Capacity of Inpatient Hospital Beds and Critical Care*** | DES or SD for models of resource requirements;<br>HS combining DES models of hospital operations and SD model describing the progression of the epidemic. | ***Decisions 1/2***<br>(ICU arrival rates). | ***Decisions 1/2***<br>(Hospital death and survival rates). | COVID-19 ICU Preparation Simulation (Stephenson 2020). |
| | | ***Decisions 9/10***<br>(Admission and Discharge rates for COVID and non-COVID patients). | ***Decisions 9/10***<br>(ICU beds and resources based scenarios to feed into experimentation design). | |
| ***7. Staffing*** | DES models of hospital operations;<br>SD models to represent workforce availability at a national level. | ***Decisions 1/2***<br>(ICU arrival rates). | ***Decisions 9/10***<br>(Workload based scenarios to feed into experimentation design). | COVID-19 ICU Preparation Simulation (Stephenson 2020). |
| | | ***Decisions 9/10***<br>(Admission and Discharge rates for COVID and non-COVID patients). | | |
| ***8. Management of Resources within a Region*** | SD or DES models of logistics and supply chains;<br>ABM for behavioral models of individuals. | ***Decisions 1/2***<br>(Demand levels for food and PPE resources and People buying rates) | | |
| | | ***Decision 4***<br>(Demand levels test equipment and logistics). | | |
| | | ***Decision 5***<br>(Demand levels vaccination equipment and logistics). | | |
| | | ***Decision 11***<br>(Demand levels for social care). | | |

Table 1: (cont.) List of COVID-19 related decisions (Currie et al. 2020) and their input and output linking variables with related decisions.

| Decision | Suggested Modeling Methods | Receives variables from: | Sends variables to: | Model(s) available online |
|---|---|---|---|---|
| ***9. Investigation of the Thresholds for Admission and Discharge of Patients*** | DES for operational models;<br>SD for a more strategic view. | ***Decision 6***<br>(ICU beds and resources based scenarios to feed into experimentation design). | ***Decisions 6/7***<br>(Admission and Discharge rates for COVID and non-COVID patients). | |
| | | ***Decision 7***<br>(Workload based scenarios to feed into experimentation design). | ***Decision 10***<br>(COVID patients management patterns). | |
| ***10. Minimizing the Impact on Other Patients*** | DES models of operations;<br>SD for feedback on rationing care. | ***Decision 6***<br>(ICU beds and resources based scenarios to feed into experimentation design). | ***Decisions 6/7***<br>(Admission and Discharge rates for COVID and non-COVID patients). | COVID-19 ICU Preparation Simulation (Stephenson 2020). |
| | | ***Decision 7***<br>(Workload based scenarios to feed into experimentation design). | ***Decision 9***<br>(non-COVID patients management patterns). | |
| ***11.Health & Well Being*** | SD models for population-wide impacts;<br>HS combining SD and ABM for population-wide impacts. | ***Decision 1***<br>(rates of people in isolation and shielding). | ***Decision 8***<br>(Demand levels for social care). | |
| | | ***Decision 2***<br>(rates of people in lockdown). | | |

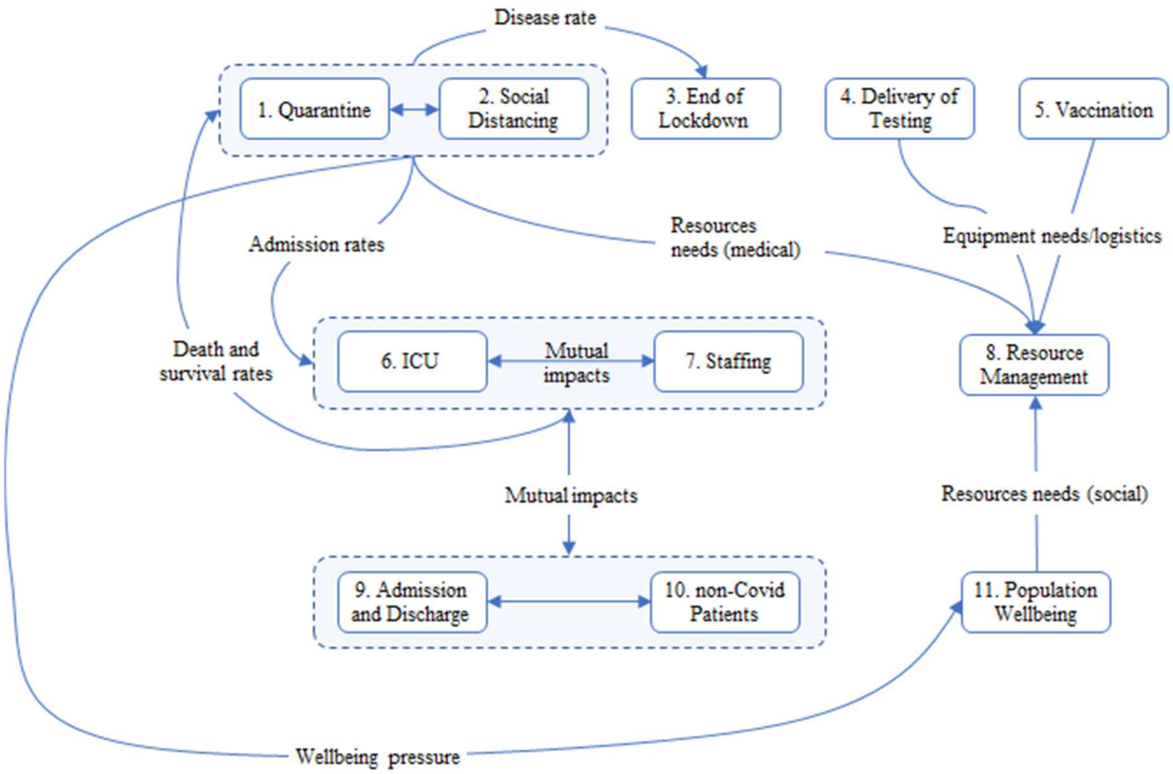


Figure 1: Potential links and their variables between the different models for COVID-19.

## 5 EXAMPLE OF HS BASED ON ONLINE MODELS

In this section we present an example of how a simulation model could be developed based on the discussion in the previous section. As mentioned earlier, time is always critical during disasters while building HS models usually takes longer time than usual in addition to the fact that there is no guarantee that there is expertise available for multiple methods. HS is vital for supporting decisions to fight COVID-19 or similar disasters due to the interconnected nature of the pandemic in terms of its behavior, logistics of treating it, in addition to the wider impact on the whole care system. To cope with this challenge, we show in the example below how a public health model for assessing the impact of various policies on managing the disease with a hospital model for ICU operation management. In this example Model 1 is a SD population SEIR model (Decision 1) with various inputs including infection rate, symptomatic rate, hospitalization rate, survival, and death rate (Fiddaman 2020). The outputs from this model could be the number of infected people, hospitalized, and survivors. Model 2, on the other hand, is a DES model of ICU beds management system. Its input is based on arrivals of patients, severity of disease, and staffing and resources including numbers of beds. The main outputs are average death and average survival levels. The purpose of the model is to experiment with different scenarios to avoid system overcapacity. Model 1 is developed by Fiddaman (2020) as part of Vantana Systems™ while Model 2 is developed by Stephenson (2020) as part of Simul8™. Figure 2 shows how the two models are linked to develop the HS model using the linking variables derived from Table 1. As can be seen from the figure, the number of serious cases needing ICU beds in Model 1 are sent to Model 2 in a form of arrival rate. On the other hand, the output from Model 2 in terms of deaths and survival numbers are sent to Model 1 in a form of fatality rate. Both models are developed independently and both are available to download and use. To build a HS model, any user can change the current settings in the models and link them. Due to lack of dedicated automated data transfer processes between different modeling software, currently, the only way to link these models (e.g., connect the receiving and sent data) is to use manual means, such as copying the data into a spreadsheet and feeding it into the destination package (Brailsford et al. 2019). While extraction of data might use automated approaches to a certain extent, it is still a mostly manual process to extract and input data from one model into the next.

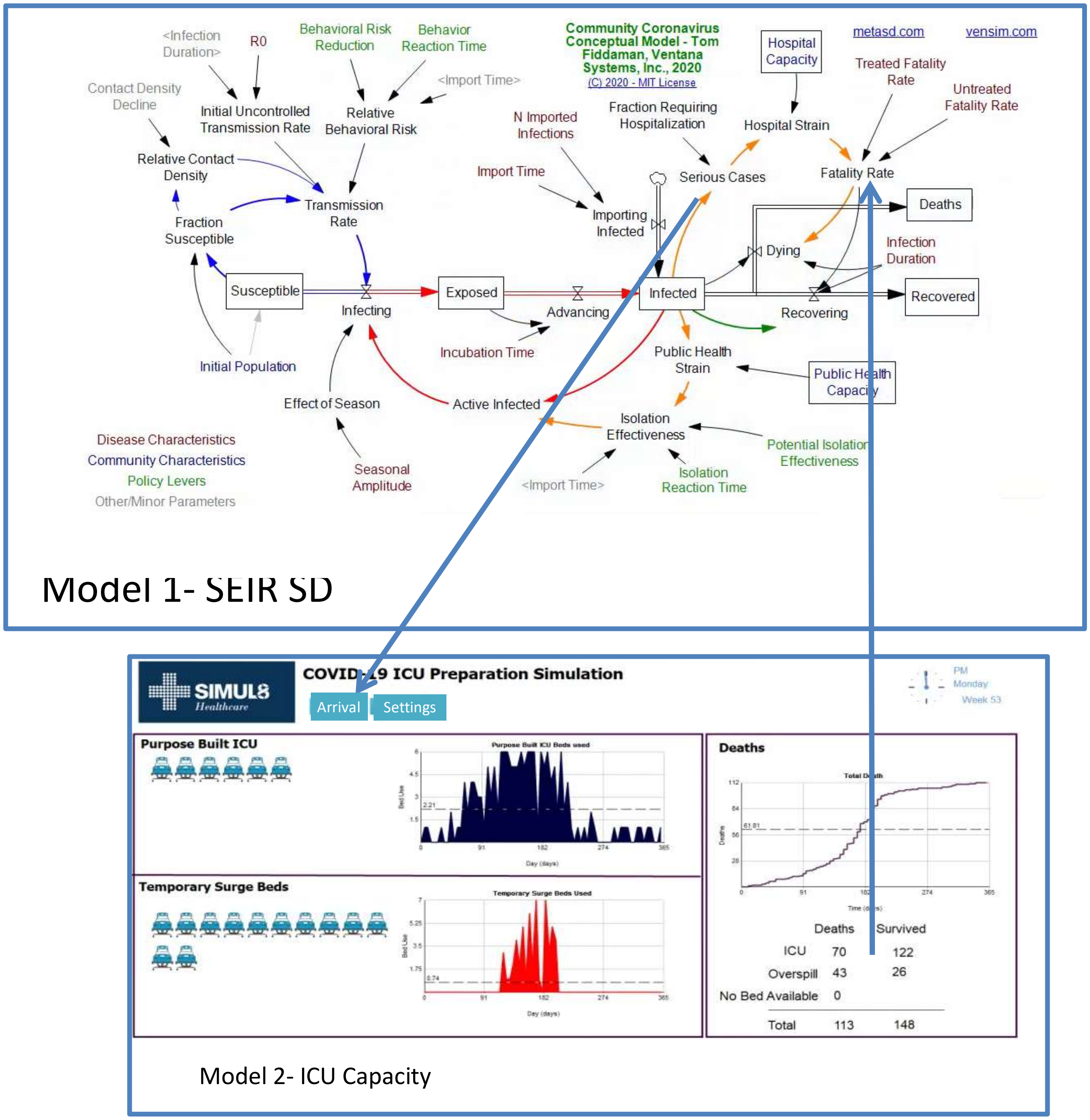


Figure 2: Hybrid simulation of COVID-19 policy model and ICU management model.

## 6 RECOMMENDATION, LESSONS LEARNED, AND FUTURE WORK

The type of complexity of each system creates the basis for scope and modeling methodology, however the COVID-19 pandemic creates a new set of problems for use of modeling, where 'knock-on' effects can create new dynamics previously not in scope of a single model, such as impact on care and treatment of cancer patients during the pandemic (Mayor 2020) or compounding public health issues like overdose surges (Wakeman et al. 2020). In the following sections, we discuss how we recommend hybrid simulation be used to aid policy makers and healthcare administrators.

## 6.1 Immediate Work

Immediately several initiatives need to converge to aid decision-makers and to support the infrastructure needed for realizing the potential of hybrid simulation. These are discussed below.

### 6.1.1 Rapid Prototyping to Face Current and Pending Challenges

Modeling experts first need to face the current challenges of the pandemic. That is, the response to the current and pending conditions of mitigation, preparedness, response, and recovery such as the disaster operations management (DOM) Framework (Altay and Green 2006). Each country, state, municipality, and health system will face different pending challenges as time moves, thus global approaches would need to consider multiple stages of the pandemic. Rapid development of models to address immediate challenges is recommended by many to be as simple as possible (Currie et al. 2020; Robinson et al. 2014) and should be the first focus to get the best information in the short term.

There are many current initiatives throughout the private and public sectors connecting researchers, public health experts, healthcare administrators, and the public to support these rapid prototypes. Of these initiatives, several are focused on education of the public, to help them understand the impact of social distancing measures and to explain the science behind public health measures. Others are initiatives focused on bringing experts together and to ensure open access to the latest datasets, models, and knowledge. Some of those initiatives are COVID-19 Healthcare Coalition (2020); COVID-19 Simulation and Modeling Task Force (2020); The Operational Research Society (2020); and The Royal Society (2020) to name a few. These initiatives have found recent momentum to share resources and educational materials to help current decision makers and inspire future experts in simulation and modeling. We as a research community will need to keep our eye on the goals of these initiatives to maintain them throughout recovery and in the future so that we are able to make the best decisions as early as possible in future pandemic and disaster scenarios.

### 6.1.2 Open Rapid Hybrid Simulation

As people begin to feel comfortable with the state of the pandemic and regions find containment, there will be a lack of momentum for model updating and data upkeep. Thus, immediate work is needed to create the infrastructure to support information exchanges between models and to maintain the integrity of the information. This is important for current usage and future use cases. This needs to involve open model content to support rapid hybrid simulation. As we have seen in this pandemic, rapid models have typically been simple so as to be developed and deployed quickly. As demonstrated in our example, using hybridized simple models to serve current needs would offer far better outcomes than single complex models. To this end, an open rapid hybrid simulation hub would need to support various aspects of models including conceptual models and assumptions. Thus, we recommend any hub to include the expert individuals themselves who can address these details and lead to better documentation of models and their data and support collaboration for new hybrid model development.

### 6.1.3 Develop Simulation Modeling Standards for Open Access

As a simulation community, we need to come together to develop standards for how to deliver these open source elements (data, models, and model elements). A hub will need consensus among contributors and users on the standards developed. We can look to other industries for models on standards development, where an industry comes together to tackle large problems such as the USB consortium (USB 2020) and the Building Information Modeling Standards (buildingSMART alliance 2020). This group will need to be broader in scope than one industry to tackle the large public health issues of a pandemic, and should include a cross section of private and public sector public health experts in addition to academics and industry members invested in simulation and modeling.

### 6.2 Future Work

For the longevity of simulation and modeling efforts for public health crises, several longer-term initiatives need to be addressed, mainly, how to incorporate new model paradigms and how to incorporate new techniques into hybrid simulations. Addressing these key aspects will ensure that a hub will be able to stay up-to-date with the latest trends across theory and application in the simulation and modeling research.

#### 6.2.1 Integrating Additional Models

While challenges still exist for the development of hybrid simulations that use SD, ABS, and DES, it is important to look to the future for incorporating other simulation paradigms. These can be simple statistical models or more complex analytical models. The simulation and modeling community can look to other large-scale problems, such as weather models and climate models to identify methods for leveraging various scaled models for different levels of detail. In addition to new models, the ability to incorporate new solution heuristics (metaheuristics, machine learning, etc.) and new analytical techniques (ranking and selection, verification, validation, etc.) need to be considered. Models will need new analytical techniques as well as new verification and validation procedures in an open hybrid simulation hub. Models may also connect to real-time data analytics - sometimes discussed in the Information and Communication Technology domains including the Industry 4.0 (Lu 2017; Wang et al. 2016) and Digital Twin literature (Boschert and Rosen 2016; Schleich et al. 2017).

## 7 CONCLUSIONS

In this article we discussed the importance of hybrid simulation (HS) in the fight against COVID-19 and its ability to connect multiple decisions categories. A major challenge facing HS is that it usually takes longer to build while requiring multiple expertise. To this end we proposed the establishment of a hub for rapid HS model development through global collaboration of simulation modelers. In the lack of such hubs, we have illustrated its potential through a simple case of HS where two models, one model, a SD disease transmission model, is connected with a DES model of a hospital ICU system. The benefits of linking these different models is clear: (1) each model can enhance the other by dynamically updating and learning from one another; (2) modelers will be able to exercise more experimental control over variables which are otherwise treated as exogenous random variables; (3) the model would act as a medium of communication between multiple experts who are collaborating to tackle COVID-19.

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