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SYSTEMIC CHARACTERISTICS TO SUPPORT HYBRID SIMULATION MODELING

Tillal Eldabi

Department of Business Transformation
Surrey Business School
University of Surrey
Guildford, Surrey, GU2 7XH, UK

ABSTRACT

Hybrid simulation (HS) is a modeling approach based on combining System Dynamics, Discrete Event Simulation, and/or Agent Based Simulation into a single model. There have been many benefits identified for utilization HS for planning and decision-making across many sectors. However, the lead time and skills requirements for developing HS models is usually greater than single methodology models. This position paper proposes that in order to improve and speed up the development of HS models, the decision to hybridize should be taken at the earliest possible point, i.e. when investigating the system and defining the problem. To this end, five system based characteristics have been proposed as decision points that help modelers to make such decisions. The paper concludes by suggesting a number of research avenues to follow for further improvements, whilst highlighting further challenges related to the availability of skills and tools for developing HS models.

1 INTRODUCTION

There are three main simulation approaches: Discrete Event Simulation (DES), System Dynamics (SD), and Agent Based Simulation (ABS). These approaches sometimes struggle with modeling complex systems when used separately. Hybrid Simulation (HS) emerged as a strong candidate to overcome such challenges (Zulkepli and Eldabi 2015). Examples of how HS is deployed and used to cope with complex systems are widely reported (Brailsford et al. 2019; Tolk et al. 2021). HS aspires to utilize the corresponding characteristics of various simulation approaches in a complimentary manner. There are several challenges reported in Eldabi et al. (2018) that hinder better effective utilization of HS. These include the ad hoc nature of current HS models (Lamé and Simmons 2018); the lack of platforms to automatically link the different models (Brailsford et al. 2019); the lack of standardized HS conceptual modeling methodology (Eldabi et al, 2016); in addition to the high cost of using more than one license based packages (Brailsford et al. 2019). Complex problems such as COVID-19 and its wider economic and social implications led to HS to be viewed as a necessity rather than a luxury endeavor. In the same time, the heightened need for HS exposed further challenges, specifically in relation to the lead time to develop a HS model and the availability (or lack of) of eclectic expertise. For the latter, Lather and Eldabi (2020) advocated the need to utilize cooperative modeling communication by way of developing a modeling hub that will support rapid development of HS models. This article aims to focus more on the modeling lead time by investigation the timing of the decision to develop HS (i.e. to hybridize or not). Many of the current frameworks suggest that the earlier a decision is made on utilizing HS (or not) will be better and will ensure a speedier model development. Whilst this paper agrees with this general stance, most of these frameworks rest the hybridization decision within the modeling domain, i.e. after the problem is well defined. However, the process of modeling, including thinking about hybridization, starts when reviewing the system to be

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modeled. Another issue that is seldom discussed, is that most modules tend to be based on the structure of the system. Modules are usually divided based on departmental segmentations such as A&E and hospital wards or pathways. Modules should not necessarily follow the process structure of the system. Rather they should be based on the relevance of the system to the modeling approach. Models should cross the boundaries of the physical systems if required. Therefore, this paper proposes further improvement to the hybridization process by attempting to identify system's features that helps in figuring out whether a HS model is required or not. To this end, this paper proposes and uses five system based characteristics as the platform for deciding on hybridization. The next section provides theoretical foundations for the main position of the paper. This is followed by the main idea of the proposed idea, detailed definitions the system's characteristics, and how it can be incorporated with one of the existing frameworks. The paper concludes by setting out a number of research avenues for enhancing the process of HS model development.

2 THEORETICAL BACKGROUND

The decision to hybridize simulation models should not be taken likely. Developing HS models is more expensive and more time consuming when compared to single approaches. This is mainly due to the fact that a HS model has to be built on top of developing two or more models and then linking them. Another issue, that constitutes a major stumbling block, is the availability of eclectic expertise (Lather and Eldabi, 2020). If, for example, the problem requires the development of a HS model by joining a DES model and an ABS model, then this necessitates the existence for expertise for developing both models. Currently, most modelers possess skills in one approach (mainly focused on one approach). There are very few modelers who have multiple skills or in teams with such variety. Such a situation is not a very common. Another issue to consider is that in rapidly moving scenarios, such as in COVID-19, building a HS could take longer than the problem lead time (Lather and Eldabi, 2020). To speed up the process, Chahal (2008) stresses the importance of making the decision on hybridization at the earlier stages of modeling. According to Brailsford et al (2019), the current trend in developing HS seems to be more coincidental where decisions to hybridize arise later into the development process. This is usually quite costly and leaves less resources for developing an appropriate hybrid model. Hence, leading modelers to make use of the existing models in an ad hoc way, resulting in less than optimum models. Therefore, and to make the best use of the potentials of HS, it is vital to make the decision of whether to hybridize or not during the problem formulation phase (Zulkepli and Eldabi 2015).

In order to make a sound choice between single approach modeling and HS, a number of researchers have proposed some frameworks to aid the decision process and guide through HS modeling process. For example, Chahal and Eldabi (2008) propose a framework that is made of three stages: determining the necessity of HS; identifying the relationships and interaction points; and defining the modes of interactions. In this framework, the decision to hybridize is derived using the objectives of the simulation and figuring out whether this can be achieved using just one approach or a set of independent models (i.e. not interlinked). The framework, which only focuses on SD and DES, was later expanded by and Zulkepli and Eldabi (2015). Helal et al (2007) propose a framework at hybrid modelling in manufacturing. This framework is mainly focused on developing a controller to link strategic levels in decision making using an SD model and tactical and operational levels represented by a DES model. Most of these frameworks, and others that followed, have emphasized the importance of how to hybridize but not much on the decision to hybridize and, more importantly, its timing. In an effort to reduce the lead time for developing HS models, this issue will be explored here. The first step of any modeling exercise is investigating the system using several methods through workshopping and facilitation in conjunction with stakeholders to understand the system and the problem (Tako and Kotiadis 2015). In order to make a decision about hybridization at the earliest possible step, this paper argues that HS frameworks need to think about the decision on hybridization at the problem definition phase. This can be part of a typical knowledge elicitation and facilitation session. The following section proposes the basic concepts of how this might be developed.

3 SYSTEM BASED CHARACTERSTICS

In this section the system based characteristics will be introduced to be discussed in detail in the following section. One thing to note here is that the proposed concept is not a replacement of current frameworks for HS development and ought to be considered in conjunction with these frameworks. It is widely accepted that the problem definition phase helps the modelers in defining the boundaries of the system and focus more on the components that lead to the modeling process. This step also includes defining the problem where issues are vague and unclear, which adds to the complexity. To this end we propose an initial step is to assess the characteristics of the system in relation to the modeling approaches. The underlining assumption is that each of the modeling approaches will be more suitable to a certain set of characteristics (see Table 1). This will help define whether a HS or a single approach is needed at the problem definition phase. For the purpose of cost and time, a single approach is preferrable. However, if the benefits of developing a HS model exceed the a single approach then the HS is developed. The most common added benefit of HS is that it will be able to provide insights which are not possible to capture using single approaches. In other words, if some of the characteristics of the system are modeled using DES while others are more akin to SD, then it would be better to develop a HS of DES-SD than to try to develop a whole DES model or a whole SD model.

In previous frameworks, such as Zulkepli and Eldabi (2015), the relevant characteristics of modeling are identified in the first phase of modeling – further explained in Sections 4.1 and 4.1.1 – but after the modules have been decided. These characteristics, which are used to decide upon the modeling approach, are usually identified based on the modeling objectives. The position of this article is that the decision about the modeling approaches should be made earlier and should be based on systemic perspectives. That is to say, the nature of the system, or how it is perceived, and its relevant characteristics should be the main driver for the modeling choice.

3.1 System characteristics for hybridization

There are a number of attempts to identify the system based characteristics. For the purpose of this paper, the characteristics will be based on those proposed by Behl and Ferreira (2014), albeit significantly modified and added to. According to Behl and Ferreira (2014), each system can be defined by a set of characteristics that provide the blueprints for any problem solving process. Five characteristics have been adopted here: Complexity, System View, Components, Behavior and Relationships. The characteristics are defined in the following sections.

3.2 Complexity

The use of HS is highly correlated with modeling complex systems. Complexity comes in different shapes and forms, in this paper the concept of complexity is divided into three main categories: Structural Complexity, Dynamic Complexity, Emerging Complexity.

3.2.1 Structural Complexity

Structural complexity is about the quantity of components – defined in Section 3.4 – within the system and whether the system is made of a high volume of interconnected components that may behave in a random – yet in a manageable – fashion. This type of system is mainly process oriented with input/process/output frame. A typical purpose of simulation here is to capture the intricacies of these components aiming to gain a certain understanding of the overall workings of the systems when such components interact over time. Generally, the components of the systems are heterogenous but behave in a controlled fashion and within bounded variability. Examples of such systems are sophisticated supply chains, patients pathways, and shipping ports.

3.2.2 Dynamic Complexity

Dynamic complexity is particularly concerned with the impact of the dynamics of the inter/relationships and feedback loops to other components that may not be exiting in a logical sequence. For example, structural complexity may consider the right sequence of components in the system (e.g. warehouses and depots), while dynamic complexity could be for viewing the impact of change in one aspect in the system on others (e.g. impact of rise of price on sales levels). The challenge of the dynamic complexity is that such links can only be explained with expert opinions rather than data. Dynamic complexity may or may not be concerned with the homogeneities of the entities in the system but usually is better viewed holistically without the need to be drawn into the structural intricacies of the of the system.

3.2.3 Emerging Complexity

In a fast-paced environment, and in systems where there are some elements of social interactions, there is bound to be change in the structure and dynamics of the system. This usually leads to emerging phenomena and untended consequences. It may also lead to behavioral changes within the components of the system to allow for better goal achievement opportunities. Decision makers may wish to enforce certain changes to the system leading to clients changing their ways in an expected manner. The challenge in this type of complexity is the unpredictability of feedback loops by individual entities who are autonomous decision makers.

3.3 System View

Each system has several perspectives depending on who is making the decision or in charge of the modeling exercise. For example, an operational manager will be interested in identifying bottlenecks within a certain supply chain. On the other hand, a district manager will be interested in identifying the impact of sales decision and bullwhip effect. That is to say, modelling a certain system is highly dependent on the purpose of the model and the position of the view of the modeler. There are three possible system perspectives:

3.3.1 Centralized micro-level view

This could be a macroscopic view combined with the need to assess individual actions in aggregate or uniform behaviors. The most important issue here is that the view of the decision maker is centralized with no freedom allowed for individual entities. For example, cars waiting in a traffic light are allowed to move when the light is green or amber and halt when the light is red. Regardless of the intelligence capacity of the individual entities, they all have to abide by centrally imposed rules. In a system such as this one, the decision maker may be interested in finding the optimum light changing times to achieve the best waiting times for individual cars.

3.3.2 Wholistic Macro-Level view

In this case the decision maker will be looking at the overall behavior of the system in aggregate manor without specifically recognizing individual components. Using the traffic light example, decision makers may be interested in the overall flow of traffic and its impact on environment within a certain locality or the overall traffic flow in part of a city. There is not much emphasis on control, as this could be a centrally controlled closed system such as the traffic light system or an open uncontrollable system such as the weather system. What is important is the ability to observe and understand the dynamics of the system via the model.

3.3.3 Bottom up View

Although modelers and decision makers are usually viewing the system from top down, they may be interested in assessing how the components behave within the system in response to external or internal changes. In such cases, individual components will have some sort of autonomy or could behave in controllable way and the system is then driven by heterogeneous individual entities. This may not be the case at a specific traffic light point, but some cars may decide to reroute their journey depending on advanced warnings of traffic issues. Similarly to the above type, there is not much emphasis on control, as it could be a centrally controlled or an open system The most important issue here is the need to assess or explore unknown reactions by individual components.

3.4 Entities/Components

Entities in the system are parts with objective and physical reality and may possess certain properties. Depending on the type of system, entities can be interpreted as individuals or groups and can be passive or have active autonomy. In top down views, entities can be treated individually or aggregately, however, they do not have the autonomy to make decisions. Individual entities may have the ability to make decisions or behave in uncontrollable fashion. This is mainly the case for bottom up view systems views.

3.5 Behaviors

All simulated systems tend to follow a certain pattern of behavior. The importance of behavior is based on changes to components over time and that what differentiate simulation from other modeling approaches. Systemic behavior is based on the behavior its components. There are three possible types of behaviors for each systems, which are discussed below:

3.5.1 Logical Flow Behavior

Logical flow behavior is concerned with components that behave based on a set of sequentially ordered events. The logic and order of these events is usually centrally preplanned. Each event can trigger the starts or ends of activities, this is how time is consumed in such systems. Event based activities usually follow a certain protocol and can also be planned to follow a certain sequence. The duration of each activity may or may not be predetermined. Examples of predetermined activities are supply chain activities and patient pathways (a start of a treatment regime).

3.5.2 Fluid Behavior

In this type of system, there are no specific events associated with specific components or entities. As there are no specific events then there are no specific activities associated with these components. Here, time is consumed uniformly showing an overall behavior over segments of time. Disease spread in a population over period of time (e.g. a month) is an example of such system. In this case no event of a patient catching the disease or becoming a carrier needs to be considered. The direct comparison between logical flow behavior and fluid behavior is that the first type, time is punctuated by discrete events while for the latter, time passes continuously and independent of individual changes.

3.5.3 Triggered Behavior

In this case, a component's behavior is triggered by changes to the endogenous interests of the component or by externally surrounding factors and other components. In this case components change state into active or passive behavior. Active behavior means that the component is engaging in transactional activities with other components. Passive behavior means a change of the state of being of the component without engaging in activities, such as a change of feelings or the nature of disease, that may lead to change of the course of actions at some point in the future. All changes are usually triggered by components based on the current state of the system rather than following predefined logic. It must be noted that it is possible to trigger activities here through central control but individuals may react unpredictably leading to a newly emerging group behavior.

3.6 Relationships

Most systems have a set of specific inputs and outputs. The nature of the relationships between the input variables and output variables at the system level represent a major factor in the choice of the modeling approach. There are three types of relationships: Linear Relationships: these types of relationships can be expressed using linear equations; Nonlinear Relationships: these can be expressed in nonlinear equations or may not be traceable; Networked Relationships: these types are more akin to network analysis. Networked relationships may also be expressed in linear and nonlinear fashion with interlinked (correlated) inputs variables and interlinked output variables and could change links as the model progresses.

4 SYSTEM CHARACTERSTICS AND MODELING APPROACHES

In this section a light touch review is conducted on the main elements of modeling from a system perspective. The main purpose is to attempt to identify how the three modeling approaches can be related to the abovementioned system based characteristics. This will be the main driver for selecting a certain method of modeling. The decision of developing a HS model will depend on the lack of overlapping or the cost of using one approach is higher than splitting it into two or more methods. Table 1 provides the outcome of the comparison while the following subsections to describes each of the comparison criteria.

Table 1: Mapping Systemic Characteristics on Simulation Methods.

Characteristics	DES	SD	ABS
Complexity	Structural Brito, et al. (2011)	Dynamic Brito, et al. (2011)	Emergent Nasirzadeh (2018); Siebers (2010)
System View	Centralized Micro Level Morecroft and Robinson (2005); Brito, et al. (2011); Helal et al (2007); Tako and Robinson (2009)	Wholistic Macro Level Morecroft and Robinson (2005) Brito, et al. (2011) Helal et al (2007) Tako and Robinson (2009)	Bottom up View Nasirzadeh (2018); Siebers (2010)
Components	Passive entities, queues, activities and attributes Morecroft and Robinson, (2005) Brito, et al. (2011); Helal et al (2007); Tako and Robinson (2009)	Passive volumes, stocks and flows Morecroft and Robinson, (2005) Brito, et al. (2011); Helal et al (2017); Tako and Robinson (2009)	Active Autonomous Nasirzadeh (2018); Siebers (2010)
Behaviors	Logical Events Morecroft and Robinson, (2005); Brito, et al. (2011); Helal et al (2007); Tako and Robinson (2009)	Fluid Morecroft and Robinson, (2005); Brito, et al. (2011) Helal et al (2007); Tako and Robinson (2009)	Triggered Nasirzadeh (2018); Siebers (2010)
Relationships	Mainly Linear Helal et al (2007)	Mainly Non-linear Helal et al (2007); Robinson (2009)	Mainly Networked Nasirzadeh (2018); Siebers (2010)

4.1 Hybrid simulation revisited

In this section will revisit an existing framework, proposed in Zulkepli and Eldabi (2015), and show how the system based characteristics discussed in the previous section could be added to work along, with some modification, the modeling steps. Zulkepli and Eldabi (2015) proposed a HS development framework based on initial work by Chahal and Eldabi (2008). The framework is based on three main phases: Conceptual Phase; Modeling Phase; and Models Communication Phase. The focus of this paper will be on the first phase where the system based reviews should take place. Once the models are decided, Phase Two and Three will be the same.

4.1.1 Current Phase One Steps

Phase One of the current framework is made of three steps as detailed below:

Step One: Problem Source Definition and Objective(s) Identification. This is a typical step and is performed for all simulation models to define the problem and the need for hybridization.

Step Two: Conceptual Modeling and Modularization Process. This step aims to subdivide the conceptual model into several modules, each of the modules contains a standalone process. Each of the modules could be a model of a certain subset of the grand model (e.g. clinic, social care, A&E, surgery, etc.). It may also subdivide the same model into further dimensions, for example, a patient model and a doctor model.

Step Three: Identification of the Characteristics of each Module. The purpose of this step is to identify the characteristics of each module to decide which technique is suitable for modeling the respective module. Such characteristics are: short- (or long) term effect; type of analysis (individual or aggregate), feedback requirement etc. Modelers could resort to well-established characteristics used to define the three main simulation approaches i.e. DES, SD, or ABS. The identification of the characteristics and requirements for each module will lead to deciding which approach to follow. Figure 1 provide a flowchart of Phase 1 process for the current framework.

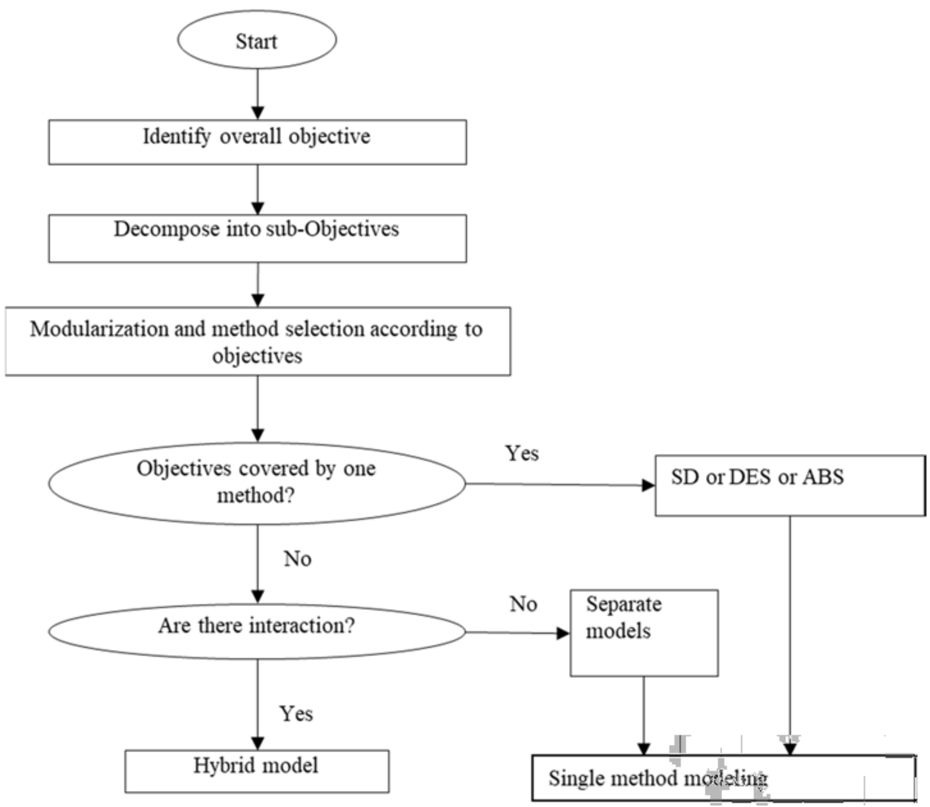

Figure 1: Current Framework Phase 1.

4.2 Modified Phase One

In the above framework, it can be seen that the decision to hybridize is based on subdividing the problem itself into modules and then identify the relevant modeling approach for each module. One criticism on this approach is that it is possible that the problem may not lend itself to subdivision. There is no mechanism to ensure that modular objectives will lead to achieving the overall problem objective. However, the modularization process in its own right is a beneficial one.

Following the systemic review process, introduced earlier in this paper, this step is proposed to be added just after, or part of, the problem definition step. The system review process will help identify and/or suggest the modeling approaches required for the different parts of the system in accordance with their characteristics. The modularization step could then take place to link the right approach to the right module which is already identified. The added benefit of this approach is that modules could take different dimensions and not necessarily following the process structure of the system.

4.2.1 Proposed New Steps

Given the above modifications, the steps within Phase One are inevitably changed from those described in Section 5.1 and are given below:

Step One: Problem Source Definition and Objective(s) Identification. This is a typical step and is performed for all simulation models to define the problem and the need for hybridization. There is no change to this step.

Step Two: System based Review. This step is added to reflect the systemic review process introduced in this paper. The purpose of this step is to identify the characteristics of the system and map them onto the three modeling approaches. In this step, modelers will be able to decide whether a HS model is unavoidable or not. They will also be able to identify what the modeling requirements are in the different parts of the system leading to specific modules.

Step Three: Models Conceptualization for each Module. Once the models are decided for each module, the purpose of this step is draw up the conceptual models for each approach within each modules. It must be noted that, these steps are not necessarily rigid in sequence and are open for feedback loop until the modelers are happy to go to the next phase. Figure 2 provides a flowchart of Phase One process including the proposed modifications.

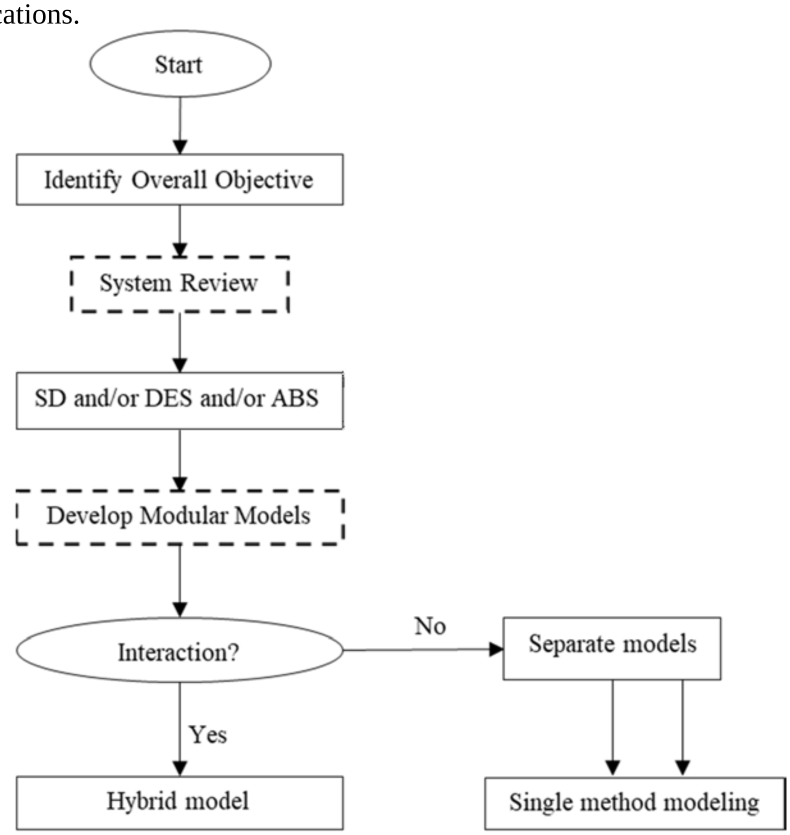

Figure 2: Proposed Framework Phase 1.

5 CHALLENGES AND ROADMAP

The modifications discussed in the previous section shift the focus of modeling towards a system based view albeit at a proposition stage and will warrant further investigations. There are a number issues to consider and further studied which are listed below.

5.1 System's Characteristics

The main tenet that HS will be a viable option forward if we have more characteristics that are relevant to two or more approaches. These characteristics will need to be evaluated and verified to assess their reliability for deciding on hybridization. The current list is effective but not exhaustive and is open for amendments. Further research is needed to investigate the viability of this list and whether more items should be added. Moreover, to ensure useful implementation, a mechanism is needed to be support modelers during the systemic review. Currently, there are a number of knowledge extraction methods during problem definition and facilitation phase. Therefore, a set of standard questions or a checklist ought to be developed to help modelers extract these characteristics from the system owners in accordance with the problem.

5.2 Coverage of Expertise

In many cases, if it is decided to develop a HS model, it is quite possible that there will not be enough expertise to cover all the aspects of the modeling (or cover more than one approach). This issue did not have its fair share of research in HS development. Most of the current researches focus on the process and viability of developing HS models with no constraints in terms of available skills and tools. In real life and as mentioned earlier, for example, in COVID-19 related situations, the modeling process has to be rapid to cope with the volatility of the situation. This could be hindered by the lack of eclectic skills. This issue needs further investigation. Lather and Eldabi (2020) propose a new way to look at this issue.

What is also missing from the list of characteristics presented earlier, is the extent to which each of the methods could cope with irrelevant characteristics. Therefore, more research is needed to assess the extent to which the approaches are overlapping in accordance with the identified characteristics. That is to say, it is possible that one approach may be able to meet the characteristics that are part of another approach. More research is needed to find out potential characteristics overlapping and how this might be correlated with the depth of expertise. For example, there is no clear understanding of whether a novice modeler will be able to utilize the existence of overlapping as much as an expert modeler and vice versa.

6 CONCLUSIONS

This paper proposes some ideas to consider as part of existing modelling frameworks for HS. The emphasis is on deciding to opt for hybridization as early as possible in the modeling process rather than stumbling upon it in the latter stages. The earliest stage to do that is when the modelers are investigating the system and defining the problem. To this end, this paper aims to contribute to the literature by first identifying and proposing a set of system related characteristics as the driving decision points for deciding to hybridize or not. These characteristics are then mapped on to the three simulation approaches to identify how they can be utilized for assessing the viability of developing HS models. This approach also removes restrictions set by existing physical and process based boundaries of the system, which are usually used to drive modular development for HS. The paper concludes by identifying two main strands of research to assess the viability of the system based review: first, finalizing and validating a viable list of system characteristics for the review; secondly, to establish the tradeoff between using a single based approach and HS using the selected characteristics given the set of skills needed.

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AUTHOR BIOGRAPHIES

TILLAL ELDABI is a senior lecturer (associate professor) at Surrey Business School (University of Surrey). He has B.Sc. in Econometrics and M.Sc. and Ph.D. in Simulation Modeling in Healthcare. His research is mostly focusing on developing frameworks for Hybrid Simulation for modeling complex systems with special emphasis on aspects of modeling healthcare systems. He developed many models and tailormade modeling packages to support health economists and clinicians to decide on best treatment programs. He published widely in highly ranked journals and conferences. He gained funding from national and international councils such as EPSRC (UK), Qatar National Foundations, British Council, and UNDP – all related to modeling healthcare or Higher Education enhancement. His email address is t.eldabi@surrey.ac.uk. His website is https://www.surrey.ac.uk/people/tillal-eldabi.