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MODELLING FOR THE TRIPLE-BOTTOM LINE: AN INVESTIGATION OF HYBRID SIMULATION FOR SUSTAINABLE DEVELOPMENT ANALYSIS

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ABSTRACT

Addressing issues around sustainable development have become increasingly vital for industries and the initial pragmatic tactic is to devise a systematic approach for improving sustainability across the organization. Modeling & Simulation (M&S) studies have been extensively applied in industries to gain insights into existing or proposed systems of interest. Despite this, the application of M&S to evaluate the often competing metrics associated with sustainable operations management is likely to be a challenge. Our paper presents a comparative analysis of the characteristics of sustainable development against capabilities of M&S techniques in order to adopt the most appropriate technique to analyze sustainable development. Triple Bottom Line (TBL), which is a widely used concept in sustainability and includes environmental, social and economic aspects, is used as a benchmark for assessing this. This paper argues that the hybrid approach leverages the capabilities of individual M&S techniques for better understanding and analyzing complex TBL-based systems.

1 INTRODUCTION

Sustainability-related research has seen an exponential increase in recent decades and continues to be amongst the fastest-growing research areas in the scientific literature. This is however not surprising considering that there is a growing body of evidence which suggests that the international community is faced with drastic environmental challenges related to climate change and global warming. Findings from research suggest that irresponsible human action, particularly at the corporate level, are responsible for some of these (Weldford 2013; Elkington 2002; McDonough 2002). It is therefore not surprising that during the past two decades there has been a significant increase in environmental awareness and of the need to reduce the impact of organizational activities that negatively impact society and the environment (Reid 2013). Organizations are increasingly conscious of the fact that their continued success is dependent on achieving a balanced outlook of three main responsibilities, namely, *Economic*, *Social* and *Environmental* responsibility, with respect to setting up their strategic priorities through the lens of the *Triple Bottom Line (TBL)* of sustainability (Gimenez et al. 2012). TBL is a framework that guides organizations towards achieving sustainable success (Aras and Growther 2013) by helping to ensure that they remain profitable whilst also fulfilling their environment and societal obligations (Tang and Zhou 2012). Synergies achieved through the TBL thus deliver a 'win-win' situation that may enable the realization of multiple interconnected aims and objectives in the economic, social and environmental dimensions.

Addressing issues around sustainable development have become increasingly vital and the initial pragmatic tactic is to understand the potential for improving sustainability across the organization. M&S lends itself to conceptual representation of a system of interest and its implementation through a computer model, and further use the computer model to experiment with strategies for improvement; as such, it is arguable that M&S could play a pivotal role in designing sustainability-related strategies since it allows the organizational stakeholders to 'experiment' prior to 'implementation'. Dealing with sustainability challenges is becoming increasingly complex and costly (Patzelt and Shepherd 2011); sustainable operations management (SOM) concepts used in tandem with M&S techniques could thus provide significant insights in coping with the uncertainty associated with TBL management (Gimenez et al. 2012).

SOM can be defined as the planning, coordination and control of a system that creates or adds value to the stakeholders in the most cost-effective manner while striving to protect the environment and respecting social values and moralities (Kleindorfer et al. 2005). Linton et al. (2007) argue that, in essence, sustainability in operations management crosses the boundaries of current conventional managerial disciplines and practices. In recent years SOM has been the focus of a plethora of studies related to operations management and management science (Linton et al. 2007). The researchers recognize significance of SOM concept as a key strategic factor in contributing to solutions to the complex challenges that are related to TBL management (Kleindorfer et al. 2005). The majority of existing research on SOM relates to literature reviews (e.g., Gunasekaran and Irani 2014, White and Lee 2009), theoretical frameworks (e.g. Seuring and Muller 2008) and case studies (e.g. Pagell and Wu 2009), with only a few empirical studies having been reported (e.g. Zhu et al. 2005). It is arguable that SOM will benefit from the use of M&S as such methods will enable stakeholders to test various strategies in the TBL sphere. However, as noted by White and Lee (2009), the potential of M&S is yet to be fully exploited in this area. Critics have argued that the concept of sustainability cannot be modeled as it is vague and not "adequately defined" (Bell and Morse 2008). However, there are several modeling techniques, including qualitative approaches like Qualitative System Dynamics (Coyle 1996), that can potentially be used to model sustainability. Indeed, the *Journal of Simulation* special issue on *'Modeling for Sustainable Healthcare'* (Mustafee and Katsaliaki 2015) has several high-quality submissions on M&S for aiding healthcare decision making that adheres to the TBL objectives. We take the informed view that SOM literature has benefited from further exploration of M&S in the context of modeling for sustainable development analysis, and it was with this intent that we have presented a literature review (Fakhimi et al. 2013). In this research, we will use this as a basis for investigating specific M&S techniques for sustainability modeling. We will present a comparative analysis of the characteristics of sustainability against capabilities of M&S techniques. This would, in return, help a modeler to adopt the most appropriate technique to evaluate TBL-based systems.

The remainder of the paper is organized as follows. Section two provides an overviews of the literature on the application of M&S techniques for sustainable development analysis. In section three we present an outline of the TBL model characteristics and map this against the capabilities of the M&S techniques. Section four identifies the gap between TBL model, system and modeling techniques and section five discusses the combined application of multiple M&S techniques (referred to as hybrid M&S) for studying TBL-based systems. Section six is the concluding section and summarizes the research contribution and provides pointers for future work.

2 LITERATURE REVIEW

There are several studies that have reported on the advantages of sustainable development on organizational performance (i.e. McDonough 2002, Reid 2013, Gimenez et al. 2012). However, from an operations management perspective, it is important that the TBL strategies are implemented in practice. In pursuance of this goal, it is arguable that computer M&S is a valuable tool in the hands of the decision makers. It allows for the experimentation of alternate TBL-centric strategies and to compare the results of the simulation in a meaningful way. M&S studies have been widely used in industry to gain insights into existing or proposed systems of interest. However, our review of literature (Fakhimi et al. 2013) shows that there has been a dearth of empirical research on integrating sustainability factors with systems' modeling studies; It is with this aim of addressing this gap that we have presented a review of literature which attempts to provide a synthesized view of M&S approaches which have previously been used to model sustainable development issues.

We found that system dynamics (SD), mathematical modeling (MM), discrete-event simulation (DES) and agent-based simulation (ABS) were the most widely applied techniques addressing sustainability issues. Every technique has a methodological foundation, for example, SD adopts a holistic systems perspective and uses stocks, flows and feedback loops to study the behavior of complex systems over time; ABS takes a bottom-up approach to modeling wherein the overall behavior of the system emerges from the underlying dynamic interaction between the agents; DES is used to model queuing systems (Mustafee and Katsaliaki 2011). Finally, MM uses mathematical notations and relationships between variables to model the behavior of a system (for example, MM approaches like linear programming and integer programming can be used for optimization). MM can also refer to statistical approaches to model system behavior, for example, Monte Carlo simulation relies on repeated random sampling from known probability distributions and which are then used as variables values. It, therefore, follows that certain techniques may be more appropriate for modeling particular classes of operations' problems. This will be further explored in section three.

Our findings suggest that *SD* is by far the method of choice for modeling sustainability with approximately 42% of studies reported in this area. This is followed by *DES*, *MM* and *ABS* which contributes to 20%, 16% and 10% of studies respectively. A further 12% have focused on the review of literature and development of theoretical framework rather than model development. Our findings also show an imbalance of treatment among the economic, social and environmental aspects of sustainability in existing studies - notably, the absence of literature that considers TBL-based modeling. How do we define such a model? We define a TBL-based model as an abstraction of an underlying system of interest that is developed to analyze the system based not only on productivity criteria (e.g., resource utilization, service time) but also on environmental and social criteria. There are five main reasons why TBL modelling is challenging: *vagueness and ambiguity, data complexity, uncertainty, difficulty in balancing TBL, and factors relating to morality and social norms* – refer to Fakhimi et al. (2013). Due to these unique characteristics of TBL-based systems, it is arguable that modelling such systems is complex!

Our findings also show that 53% of papers were published after 2010. This rise could be attributed to the increasing focus on sustainable development in industries and which may have contributed to scholarly studies on this topic. However, despite this, there is a dearth of studies on the application of M&S in addressing the TBL and challenges still remain in developing, implementing and validating models (Fakhimi et al. 2015). Developing models that respond to these complexities is not a trivial task for modelers (Chi 2000) since they require to ensure that the models are, (a) applicable to the real world, (b) consider the appropriate levels of details (Fakhimi et al. 2013), and (c) consider all three sustainable development pillars (TBL) in their analyses (Bagheri and Hjorth 2005). These assumptions need to be further investigated in the context of complex and uncertain systems like the TBL system. The modelers will benefit from understanding the definitions, assumptions, conceptualizations and also implementation constraints in this emerging field.

In summary, our research findings indicate a lack of empirical research on applications of M&S for SOM. The review of the literature has also revealed an unequal treatment of economic, social and the environmental factors among the SOM studies that employ qualitative models (e.g. conceptual models) and those using quantitative/mathematical modeling (e.g. computer simulation). While the former modeling approach has considered the three aforementioned sustainability-related factors in the formulation of guidelines, frameworks, best practices, etc., the latter has mostly ignored the societal aspects of TBL framework and has focused principally on the economy and the environment (e.g., studies on sustainable supply chain management, and life cycle assessment, etc.). Therefore, the important question here is "What is the impeding development of the TBL models?" In this paper, we try to address this gap by taking a systems approach and interrogating whether the TBL characteristics are constraints on implementing models using the widely used M&S methodologies.

3 TBL MODEL AND M&S TECHNIQUES

The purpose of this section is to present a comparative analysis of the characteristics of sustainability against capabilities of M&S techniques. This would, in return, help a modeler to adopt the most appropriate technique to evaluate TBL-based systems. For such purposes, it is arguable that a set of criteria should be considered in order to objectively select a suitable M&S technique. We identified a set of nine criteria based on, (a) characteristics of TBL-based systems, (b) our domain knowledge and (c) the limitations frequently associated with TBL models in the literature. In this research, a viable TBL-based characteristic is that models should be developed such that it satisfies all TBL responsibilities of the given system for a long-term period. An ideal model is expected to demonstrate the following criteria, (1) the M&S approach used to develop the model should be easy to learn, simple to develop and intuitive (this would encourage wider adoption among stakeholders), (2) the TBL model should incorporate characteristics that assist in making TBL-based decisions (the M&S approach usually dictates the characteristics that are present in the model), (3) the M&S approach should support visual depiction of the TBL model (this ensures that system stakeholders, who are generally not experts in M&S, get a graphical representation of the system as it advances through simulated time; the visualization would aid their conceptual understanding of the system), (4) the TBL model should represent the appropriate level of detail (at the very minimum it should include metrics associated with economic, social and environmental aspects of the system being modelled), (5) the TBL should be dynamic (this implies that the M&S approach used for modeling should include a time component and the model should be stochastic; this is in line with M&S applied in the context of operations management since such systems usually include random components), (6) the TBL model should ideally assist stakeholders to take both short-term and long-term decisions (this is in line with the characteristics of TBL-based systems since financial aspect is usually important in both the short-term as the long-term; however, environmental and society implications are arguably medium and long-run indicators), (7) the TBL-based model should endeavor to simplify complexity, uncertainty and vagueness that exists in a TBL-based system. Thus, the qualitative representation of the system that incorporated the views of multiple stakeholders will necessarily be ambiguous; however, a TBL model will need to represent this using quantitative representation thus reducing the vagueness inherent in qualitative models, (8) a TBL model should be able to deal with data complexity (such complexities exist since there are numerous interdependencies in the TBL-based system and the data reflects this), and (9) a TBL model should be able to represent different levels of abstraction since the stakeholders will look at the system through different lenses (e.g., the financial director may be interested in short-term profitability, the environment protection officer may be looking at reducing carbon emissions in 10 years timeframe, etc.). Table 1 presents the comparative analysis of the viable and ideal TBL model criteria against capabilities of four frequently applied M&S techniques for sustainability purposes.

Table 1: Mapping the TBL system criteria with characteristic of modeling technique (Adopted from Zulkepli (2012), Brailsford, et al. (2010)).

Criteria of a TBL model	**System Dynamics (SD)**	**Discrete Event Simulation (DES)**	**Agent-Based Simulation (ABS)**	**Mathematical Modeling (MM)**
Simple to model	Easy to learn and use, simple to model (Zulkepli 2012);	Easy to learn and simple to model; It will be complicated if the system is big (Zeigler et al. 2000);	Developing and using the model for a big system is very complex (Macal and North 2010);	Too complex to be applied and analyzed in managerial decision makings (Williams 2013);
Assisting TBL-based decisions	High assistance, providing estimation, what-if-scenarios and cause & effect diagram (Williams 2013);	High assistance, providing estimation, prediction and what-if-scenarios (Siebers et al. 2010);	High assistance, providing estimation, prediction and detailed what-if-scenarios (Macal 2010);	Medium assistance, proving estimation and prediction (Ibragimov and Ibragimov 2010);

Criteria of a TBL model	System Dynamics (SD)	Discrete Event Simulation (DES)	Agent-Based Simulation (ABS)	Mathematical Modeling (MM)
Visualization	More efficient for representing outside of the system rather than inside (good for macroscopic view on the system); Non-expert can still understand the whole system (Gunal and Pidd 2010);	Efficient for microscopic view on the system; non-expert can understand how the system runs (Law et al. 1991);	More efficient for representing both inside and outside of the system; non-experts may find it difficult to understand how the system runs (Siebers et al. 2010); However, this also varies based on simulation software packages that are used.	Implicit and hard to understand for non-experts, hard to see process flow and how TBL-based system operates (Aris 2012);
Dynamic Model	Provided as time included in the model; (Zulkepli 2012); Provided as a result from any intervention that has been done to the model/system (Pidd 2009);	Provided as time included in the model (Zulkepli et al 2012);	Provided as time included in the model;	They are not essentially dynamic; Mostly used for mathematical optimization.
Dealing with different levels of abstraction in the system	Mostly dealing with high level of abstraction (Jain et al. 2013);	Mostly used at low to middle level of abstraction (Jain and Kibira 2010);	Dealing with all abstraction levels (Maidstone 2012);	Cannot deal with different levels of abstraction;
Represents system at appropriate level of detail	May cover the whole system, but does not present the intrinsic details of the current system visually Holistic models have been developed in many studies for strategic modeling and supply chain modeling (Angerhofer 2000).	May cover the whole system, but it will be complicated and complexity increases exponentially with size (Angerhofer 2000);	Can develop holistic models (Hughes et al. 2012). Developed models represent the complex systems better than other techniques, however developing model showing the details in high level resolution will be complicated and the size of model will be very big;	Given complexity and uncertainty associated with TBL-based systems, availability of such data will be hardly accessible. It cannot represent the interaction and interdependencies between parts of the system;
Simplifying the complexity/uncertainty/vagueness	Simplifying complexity for the environment surrounding the system as well learning in a complex world (Pidd 2009);	Simplifying complexity for the process in the system, if system is too big, modelers tend to break down the system (Widok et al. 2011). However, such approach cannot be applied for modeling the integrated TBL-based systems (Fakhimi et al. 2015);	Simplifying the complexity of systems (Macal and North 2010);	Simplifying complexity of systems;

Criteria of a TBL model	System Dynamics (SD)	Discrete Event Simulation (DES)	Agent-Based Simulation (ABS)	Mathematical Modeling (MM)
Dealing with Data Complexity	Broadly drawn;	Numerical with some judgmental elements;	Dependent not only on data but also interaction defined between agents;	Cannot easily deal with complex (mixed qualitative and quantitative) data;
Providing both Short- and Long-term decision making simultaneously	Compared with the other three techniques, SD mainly used at a higher, more aggregated and strategic decision making (Hughes et al. 2012);	DES is stochastic and mostly is being used at more operational or tactical level to answer specific questions (Brailsford et al. 2010);	Every well formulated SD model has an equivalent formulation as an ABS model. (Agency Theorem for System Dynamics) (Macal 2010).	MM essentially will not be able to develop a soft strategic model. MM models are mathematical models that usually use types of numerical time-stepping procedure to find the models behavior over time;

As summarized in Table 1, when the single modeling approach was used, the capabilities of any one specific technique could not fully cater for all the needs and characteristics of the TBL-based system, thereby creating a gap between the system needs and the capabilities of the techniques. Section four discusses the gap between methods' capabilities, TBL systems and viable TBL models. Section five then presents suggestions on reducing this gap.

4 TBL SYSTEM, M&S TECHNIQUES AND TBL MODEL: IDENTIFYING THE GAPS

We present a conceptual representation of the relationship between M&S techniques and its underlying capability to model a TBL-system (See Figure 1). The conceptual representation is informed by our methodological study of literature in M&S for SOM. The outer circle represents the ideal characteristics of TBL systems (these need to be modeled), the inner circle represents the capabilities of M&S techniques to represent a TBL system. As can be seen from this figure, there is a gap (or divergence) between the characteristics that need to be modeled (outer circle) and those that can be modeled (inner circle). This occurs because no single simulation technique can adequately represent the characteristics of a TBL-based system. Because of this divergence, it is arguable that the existing models developed using a single M&S technique are not ideal for decision making pertaining to TBL-systems since the use of such models will result in decision making which does not fully appreciate the interplay between the factors underlining the organizational consideration for TBL. According to our findings, most of the models that have been developed for sustainability purposes use a single modeling technique. With the objective of reducing the gap between *'what is to be modeled' and 'what can be modeled',* we argue that a combination of M&S techniques, or *Hybrid Simulation, can be* used to better represent a TBL-based system, since the decision-making process that is facilitated by such models will more likely take into consideration the overarching sustainability-related themes. Figure 1 illustrates how such combined approach could reduce the divergence in modeling the TBL-based system with current modeling techniques. It is, however, to be noted that such divergence may also exist for hybrid techniques. However, we argue that the application of hybrid simulation lends itself to a closer representation of the TBL-system (when compared to using single techniques); this is illustrated by the existence of a smaller gap between *'what is to be modeled'* and *'what can be modeled'* in Figure 1. The overlap between modeling technique one and two shows that the techniques have some common capabilities (See Table 1); they also have distinct capabilities and this is shown by the area of the dotted circles that do not intersect. If follows that, the combined capability of the multiple M&S techniques contributes to the reduction of the aforementioned divergence.

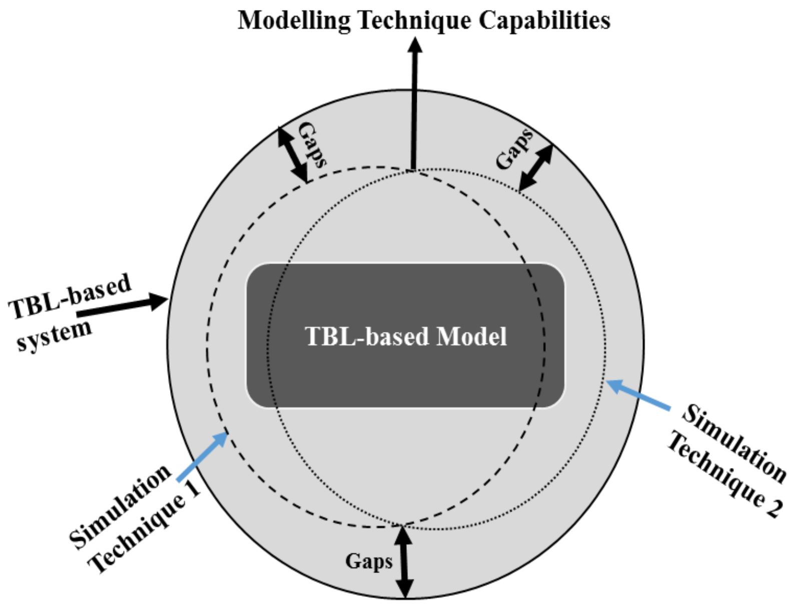

Figure 1: The gaps between system, model and technique (Adopted from Zulkepli 2012).

In section 3, we have presented a discussion on the characteristics of a TBL model and have mapped this against the techniques (Table 1). The purpose of this is to aid the simulation practitioner in selecting the appropriate combination of methods for TBL-based modeling. Based on our review of literature (including studies that are not specific to sustainable development) we find that DES-SD to be the preferred hybrid approach. With respect to modeling for sustainability, it could be argued that the combined application of DES-SD could sufficiently model a number of underlying characteristics of a TBL-based system. There have been comparative studies on SD and DES which have highlighted their technical and philosophical differences, differences in interpretation of the problems and visualization of the systems, and the difference in the way these techniques have been applied (i.e. Brailsford et al. 2010, Chahal and Eldabi 2013). The focus those studies is mostly on *'what needs to be measured?'* rather than *'what needs to be answered?'*. However, it is arguable that the latter is an important consideration for TBL modelling. Existing studies have not considered the characteristics of TBL models while selecting specific techniques; our work has built on existing research on technique selection and have applied this to TBL models. The purpose of Table 2 is to provide guidance with regard to selection between SD and DES based on the consideration of the combined view of system, problem, methodology and TBL analysis. However, using these features to design a hybrid model with the aim of analyzing the sustainability of the system requires further insights into the characteristics of the TBL based system and the methodology for designing the combined SD-DES model. As can be seen from the table, SD-DES combination offers significant benefits to the TBL modeling objectives. This does not, however, suggest that other techniques are not appropriate; indeed, further research is needed to investigate particular combinations in relation to modeling the TBL dynamics.

In summary, the complexity and uncertainty of TBL systems being modelled, together with the representation of multi-levels of abstraction (strategic and operational) as well as multidisciplinary relationships between TBL pillars may mean that combining M&S techniques could enable the symbiotic realization of the strengths of individual techniques, while reducing their limitations, thereby potentially realizing synergies across techniques and facilitating greater insights to problem-solving.

Table 2: Criteria for Selection between SD and DES for TBL modeling.

Criteria	DES	SD
Problem Perspective		
Purpose	Productivity based decisions: TBL based optimization, comparisons and comparison	TBL monitoring: strategic decision makings and learning
Problem Scope	Productivity related operations	Strategic
Importance of randomness	High	Low
Importance of interaction between TBL KPIs	High	Low
TBL system's Perspective		
System View	Detailed view	Holistic view
Dealing with complexity	Detail complexity	Dynamic complexity
Evolution over time	Event-based	Continuous
TBL Analysis Perspective		
Required level of Resolution	Detailed individual level	Aggregate high level
TBL impact	Short-Term	Long-Term

5 DISCUSSION

The hybrid approach is not a new concept in M&S (Mustafee et al. 2015). It has been applied in studies where a single technique could not sufficiently represent the underlying complexities of the system (Sachdeva et al. 2007, Zulkepli 2012). The hybrid M&S approach has been conceptualized and/or implemented in many areas of business, such as manufacturing (Helal et al. 2007), transportation (Mustafee and Bischoff 2013), maintenance operations (Mustafee et al. 2015), environmental disasters (Jain et al. 2013), as well as in healthcare systems (Chahal and Eldabi 2013). Our findings advocate that any combined hybrid simulation for TBL analysis would need to include elements from both the continuous and discrete modeling paradigms (e.g., in the DES-SD hybrid approach, DES is discrete and SD is continuous time). This is explained next.

TBL-based systems entail dealing with different levels of abstraction; any hybrid modeling approach should, therefore, help to connect the types of modeling techniques enabling them to coexist in order to bridge the gap between the levels of abstraction. Hence, viable TBL models have to study the system from both operational and strategic levels. We argue that a simulation approach chosen for TBL modeling may include both discrete and continuous modeling capabilities; this would address both short-term changes and the long-term evolution of the system under scrutiny. The argument is further strengthened through our experience of the combined use of two discrete approaches ABS- DES (Fakhimi et al. 2014) and SD-DES (Fakhimi et al. 2015) for sustainable planning in healthcare. The findings from the former showed that the application of ABS-DES hybrid model for complex TBL-based systems could be tedious and, at some levels, prone to inconsistencies. Furthermore, it has been stated that hybrid M&S reduces the complexity, but developing a hybrid model can be very challenging (Chahal and Eldabi 2013). Thus, although SD-DES simulation is more likely to be preferred hybrid approach for TBL modeling, developing such hybrid model for sustainability analysis could be very challenging.

The challenges to TBL modeling are not limited to hybridization. The difficulty of developing models for sustainability analysis is essentially related to the complexity and uncertainty of such systems. Our findings show that such complexity appears from the early stages of the modeling exercise in the problem identification and conceptualization phase (Fakhimi et al. 2015). According to our findings, unlike productivity-based modeling, problem identification in TBL modeling does not follow linear causal principles. It may, therefore, be difficult to clearly define the problem since the variables in a TBL-based system could account for both cause and effect. Thus, in order to identify and analyze the cause of TBL problems, an overly mechanistic and linear thinking approach is insufficient and synergistic principles should be followed. The second challenge is the conceptualization of the underlying TBL-based system since it is difficult to identify the resolution of an all-inclusive TBL-based system. The next challenge raised is the identification of indicators to incorporate in such models, considering that TBL-based systems are composed of a number of quantifiable measures as also non-quantifiable indicators. It is also challenging to incorporate a TBL tolerance to the indicators in order to ensure that the system will remain sustainable even though it may comprise of a multitude of stakeholders groups with different interests, thus making it difficult to align the TBL elements towards a single purpose. For example, changing the system could show a positive outcome associated with an environmental responsibility (e.g., reduction in CO2 emission) and economic responsibility (e.g., reduction in fuel consumption) but negative impact on social responsibility (e.g., an increase in patients waiting time) (Fakhimi 2016). We have also realized that changing the system could result in both positive as well as negative impacts on the TBL pillars. Finally, a modeling scenario may show a negative outcome for one TBL pillar in the short-term, but a positive outcome in the long-term! We have therefore argued for both discrete and continuous models so as to enable us to test systems' performance against TBL framework from both long-term and short-term perspectives.

6 CONCLUSION

Sustainable development has been among the fastest-growing areas of research activity in recent decades. Despite this, M&S approaches for implementing and managing the TBL of sustainability are in their infancy. According to the findings of this research, TBL-based systems are uncertain and complex systems dealing with different levels of abstractions, where, arguably, a single modeling technique can hardly capture the requirements of a viable TBL model. In this paper, the main argument to support using hybrid simulation for TBL modeling is the need to analyze the TBL-based model at an aggregate level for long-term and at individual level for the short-term period. The assertion is that a combined simulation approach will provide a superior representation of the underlying behavior of the TBL system. Thus, the hybrid approach leverages the capabilities of individual M&S techniques for TBL modeling. The decision-making process facilitated by such modeling approach will take into consideration the overarching sustainable development-related themes. We, therefore, propose that hybrid modeling could improve the TBL models to assist decision makers for better understanding and analyzing complex TBL-based systems.

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