An Investigation into Modeling and Simulation Approaches for Sustainable Operations Management

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Modeling & Simulation (M&S) studies have been widely used in industry to gain insights into existing or proposed systems of interest. The majority of these studies focus on productivity-related measures to evaluate systems' performance. This paradigm, however, needs to be shifted to cope with the advent of sustainability as it is increasingly becoming an important issue in the managerial and the organizational agenda. The application of M&S to evaluate the often competing metrics associated with sustainable operations management (SOM) is likely to be a challenge. The aim of this review is to investigate the underlying characteristics of SOM that lends towards modeling of production and service systems, and further to present an informed discussion on the suitability of specific modeling techniques in meeting the competing metrics for SOM. Triple bottom line, which is a widely used concept in sustainability and includes environmental, social and economic aspects, is used as a benchmark for assessing this. Findings from our research suggest that a hybrid (combined) M&S approach could be an appropriate method for SOM analysis; however it has its challenges!

Keywords:

Sustainable Operations Management; Sustainable Development; Modeling & Simulation; Hybrid Modeling;

1. Introduction

We are faced with a multitude of environmental challenges related to climate change and global warming. Findings from research suggest that irresponsible human action, particularly at the corporate level, contribute towards some of these [**1**, **2**, **3**]. 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 [**4**]. 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 [**5**]. TBL is a framework (see **Figure 1)** that guides organizations towards achieving sustainable success [**6**] by helping to ensure that they remain profitable whilst also fulfilling their environment and societal obligations [**7**, **8**]. 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.

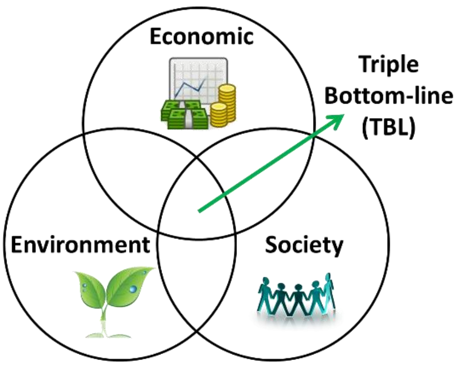

Figure 1. The spheres of sustainable development

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 [**9**]; 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 [**5**].

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 [**10**]. Linton et al [**11**] 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 [**12**]. The researchers recognize the significance of SOM concept as a key strategic factor in contributing to solutions to the complex challenges that are related to TBL management [**10**, **13**]. The majority of existing research on SOM relates to literature reviews (e.g., **12** and **14**), theoretical frameworks (e.g. **15**, **16**) and case studies (e.g. **17**), with only a few empirical studies having been reported (e.g. **18**). 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 [**13**], 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" [**19**]. However, there are several modeling techniques, including qualitative approaches like Qualitative System Dynamics [**20**, **21**], that can potentially be used to model sustainability. Indeed, the *Journal of Simulation* (http://www.palgrave-journals.com/jos) special issue on *'Modeling for Sustainable Healthcare'* [**22**] has attracted 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 will benefit from further exploration of M&S in the context of modeling for sustainable development analysis, and it is with this intent that we present a literature review and use this as a basis for investigating specific M&S techniques for sustainability modeling. We, therefore, analyze and categorize academic literature with the end goal of attempting to build a reference set of scholarly contributions. Given the topical nature of the subject, the body of literature is rather limited and, as we will learn from the literature review, some of the studies that have delved into this topic do not fully adhere to the TBL framework.

The remainder of the paper is organized as follows. Section two presents the methodology for the literature review followed by a discussion on the findings of the review. The concepts of sustainable development and challenges to the implementation of SOM are explored in section three. In section four we present an outline of the TBL model characteristics and map this against the capabilities of the M&S techniques. Section five identifies the gap between TBL model, system and modeling techniques and section six discusses the combined application of multiple M&S techniques (referred to as hybrid M&S) for studying TBL-based systems. Section seven is the concluding section and summarizes the research contribution and provides pointers for future work.

2. Literature Review

We follow the methodological review approach adopted by Katsaliaki and Mustafee [**23**], wherein scholarly databases were searched using a combination of search terms and the final set of papers were then selected by applying specific inclusion criteria. We used the *Web of Science*® (WOS) database to conduct our search; it is one of the largest databases of quality academic journals and conferences and provides access to bibliographic information pertaining to around 8500 impact factor research journals.

To identify articles that would be incorporated in our dataset the following two criteria were used: our first search string included the keywords *'sustainabl*'* AND *'simulation*'* in the article topic; the second search string was composed of *'sustainabil*'* AND *'simulation*'* ('*' is the wildcard character and is used to match one or more characters in the search string). We restricted the search to include only articles and review papers written in the English language from 1970 until 2013 (both inclusive). We further filtered the search results to include only papers indexed under the WOS subject category *'Operations Research Management Science (ORMS)';* we selected this category since ORMS is generally regarded as the field that relies on using quantitative techniques like simulation to improve operational processes and decision making. The ORMS subject category also includes topics such as mathematical modeling, stochastic modeling, decision theory and systems, optimization theory, logistics, and control theory [**24**]. Our search resulted in 205 and 104 papers respectively (309 papers in total, of which 29 appeared in both the search results). The number of unique papers was thus 280 and this constituted our preliminary dataset for analysis. The abstracts were reviewed to ascertain suitability for inclusion in our final dataset. The following inclusion criteria were used: (a) the papers were on M&S/ORMS, and (b) they included a discussion on TBL or, at the very least, discussed either the environmental or the social aspects of TBL. A critique of our inclusion strategy may be the relaxation of criteria (b) and the fact that we have also considered papers that demonstrated engagement with a sub-set of the TBL features. Although this is a valid critique, our review of literature informed us that the distinction made in papers that considered TBL and those that focused either on the environment, the economy or the society, or a combination thereof, were not always straightforward. In many papers the impact on social responsibility was implied rather than explicitly stated. In such cases, we took a flexible approach of including papers that clearly related to the problem described with some kind of sustainability impact. Applying the aforementioned inclusion-exclusion criterion we were left with 115 articles for our literature review (approx. 40% of papers from our preliminary dataset). For the purposes of informing our study on M&S for SOM, the literature review focusses on identifying the simulation techniques that have been used for modeling sustainability and to further classify these studies based on the aspect of sustainability being modeled. Section 2.1 presents the findings of our literature review.

2.1. M&S Techniques for Modeling SOM and TBL

M&S methods enable stakeholders to analyze and evaluate strategies for effective management of complex systems. It can also be used as an alternative to 'learning by doing' or empirical research [**25**]. Furthermore, M&S provides stakeholders the opportunity to participate in model development and to conduct experiments that represent real-world systems of interest [**26**]. It is therefore not surprising that M&S studies have been widely used in industry to gain insights into existing or proposed systems of interest. There are a number of domain-specific review papers on the application of M&S; there is, however, a lack of literature specific to M&S for sustainability analysis. It is with this aim of addressing this gap that we present 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 initially categorized literature based on the M&S techniques that were reported. 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 theoretical and 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 [**25**]. 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 four.

We now report on specific M&S techniques vis-a-vis their application for sustainability analysis (see **Figure 2**). 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 (reported as a distinct category in the figure below). Papers have further been classified according to the aspect of sustainable development being modeled. This is illustrated as a stacked chart that shows, under each aforementioned modeling category (and literature review), the number of studies that have considered, (a) the *three pillars of sustainability (TBL)*, (b) the *environment* and *economic* aspects of sustainability, (c) the *social* and *economic* aspects, and (d) studies that relate only to the *environment*. As can be seen from **Figure 2**, the majority of models developed using SD, MM and DES were specific to environment and economy. The literature review category also reports similar findings. Only ABS has a higher proportion of studies that focused on society and economy.

The next set of findings concern the application of M&S to model the pillars of sustainable development; here we do not distinguish between individual techniques. The findings show that only 9% of the articles have attempted to address *TBL*, while 63% have focused on the *economic and the environmental* aspects of sustainability, followed by 16% on the *environment* and 12% related to *society and economy* (See **Figure 3**). This outlines an imbalance of treatment among the economic, social and environmental aspects of sustainability in existing studies - notably, the absence of literature that considers the TBL.

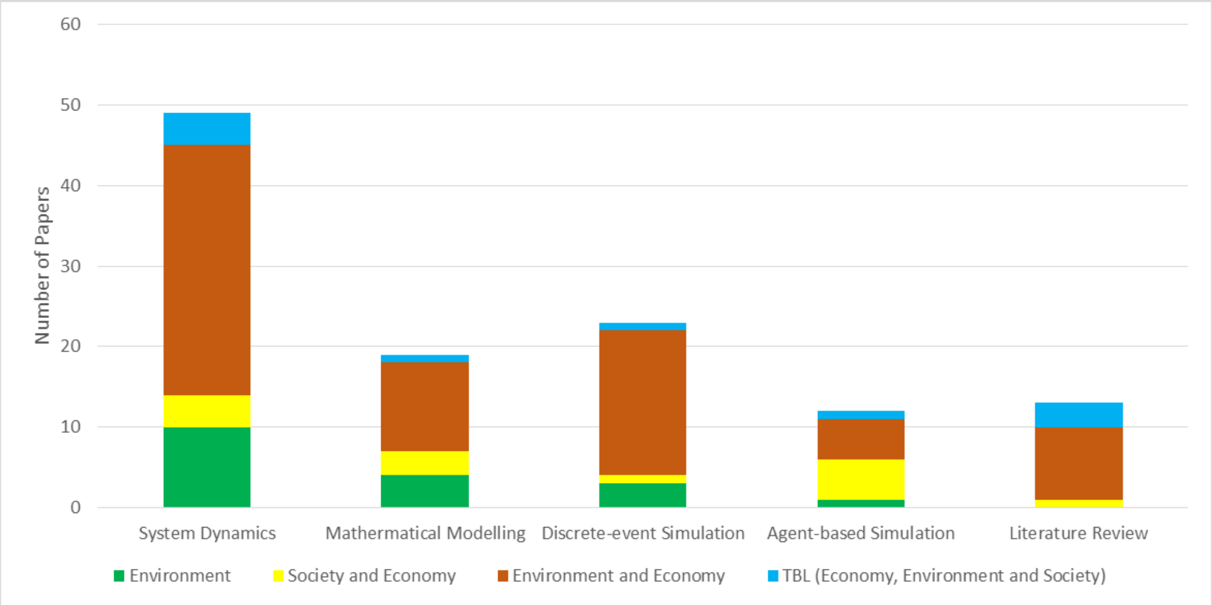

Figure 2. M&S techniques and frequency of application for sustainability analysis

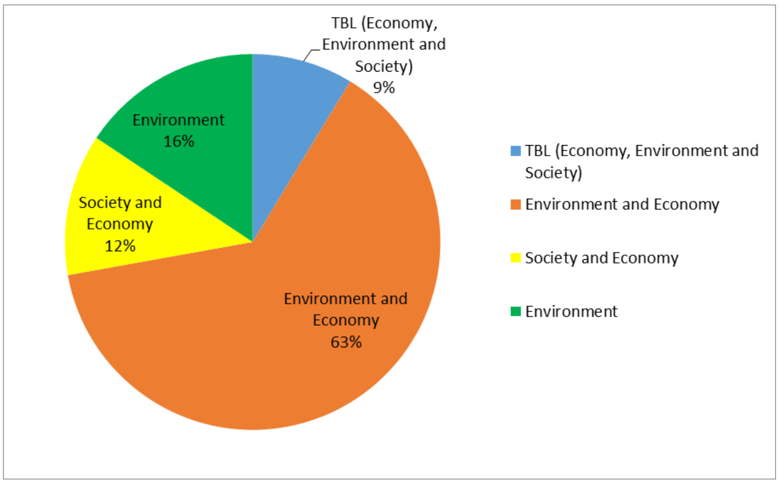

Figure 3. M&S studies that have modelled the pillars of sustainable development

Our findings 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 recent increase our findings have shown that 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 [**27**, **28**]. Developing models that respond to these complexities is not a trivial task for modelers [**29**, **30**] since they require to ensure that the models are, (a) applicable to the real world, (b) consider the appropriate levels of details [**31**], and (c) consider all three sustainable development pillars (TBL) in their analyses [**32**]. 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. The next section explores the seven main characteristics of the TBL-based system in order to analyze why modeling TBL-based system has become a holy grail [**33**] for modelers.

3. Characteristics of TBL-based System

SOM can benefit from the identification of characteristics pertinent to TBL-based systems and that is seen through the lens of a modeler. Our engagement with literature has shown that there is presently no study that has adopted such an approach. For the purposes of informing the discussions presented in the paper, the authors have thus relied on their literature review to analyze the most important characteristics of such systems, and, coupled with their domain knowledge in M&S, have identified seven important characteristics that need to be considered by the modelers in order to develop a TBL model (See **Table 1**). These characteristics are described next.

Table 1. Characteristics of TBL-based systems with references to research articles

	TBL Characteristics	**References**
1	Vagueness	i.e. [**37**, **38**]
2	Ambiguity	i.e. [**42**, **43**]
3	Difficulty of balancing TBL	i.e. [**46**, **47**, **48**]
4	Transdisciplinary	i.e. [**49**, **50**]
5	Data complexity	i.e. [**52**, **53**]
6	Uncertainty	i.e. [**55**, **56**]
7	Morality and social norms	i.e. [**57**]

(i) Vagueness

A term is vague when it does not have a specific and distinct definition [**34**]. Despite the frequency associated with the invocation of the term '*vagueness'*, the concept of sustainable development remains unexpectedly vague, indefinite, disputable, and has several variables that are hard to quantify [**35**, **36**]. Consequently, the fuzziness and irregularity in sustainable development concept have led to inconsistency and contradiction in choosing appropriate measuring indicators for analyzing sustainable development [**37**, **38**]. Although uncertainty and vagueness will always remain, it is expected that this will gradually decrease by translating sustainability concepts to quantitative models and numerical regimes.

(ii) Ambiguity

According to the Bromberger (2012) [**39**], vagueness and ambiguity have distinct properties in classical science. Ambiguous is when a term can have several definitions which could mislead the listener [**34**]. The ambiguity of the concept of sustainability has resulted in a large number of descriptions and explanations [**40**, **41**]. For example, there is no general agreement on the definition of sustainable development, despite the vast amounts of literature attempting to do so. During the period 1974-1992, for example, approx. 70 definitions appeared in literature, with the number of studies devoted to the subject continually increasing [**42**, **43**]. Therefore, it is difficult for modelers to find a 'specific since most of the discussions are led astray. This is because, first, existing interpretations ignore the range of time and space scales over which TBL models have to apply [**42**]; second, they are casting the problem as definitional while the actual problems are emerging from predictions errors [**32**].

(iii) Difficulty of balancing TBL

The basic withdrawal factor from traditional modeling approaches to departure towards sustainability analysis lies in the fact that although organizations' survival is mainly dependent on profit, the economic and financial benefits are not adequate for continuing success of organizations [**44**, **4546**]. This has raised a discussion on whether or not sustainable development is Oxymoron? [**47**]. As discussed previously, the crux of sustainable development in organizations is on an integrated three-legged stool - the so-called TBL - and success cannot be achieved by disregarding the other two [**48**]. Therefore, modeling for sustainability analysis would involve a complex web of decision-making institutions and indicators. This is because, (a) there are no comprehensive and generally accepted sets of measuring indicators for TBL-based analysis and sometimes they are very broad and exhaustive, and (b) TBL factors may sometimes hold conflicting values. Consequently, the modelers from the classic modeling disciplines cannot find a practical solution to integrate and align all TBL elements towards a single purpose.

(iv) Transdisciplinary

According to the McDonough and Braungart [**3**], everything now is connected and nothing can be analyzed in isolation. Lang et al. (2012) [**49**] also argue that sustainable development is a field that cannot be effectively explored and understood within the confines of any single discipline. Therefore, it must be embodied in some form in disciplines such as physics, engineering, ecology, law, economics, sociology, and politics [**50**]. The further that sustainable development spans across disciplines the more comprehensive its interpretation will be. Hence, this causes complicated operational and interpretational difficulties emerging from complex cross-disciplinary and multidisciplinary issues for data collection and model development.

(v) Data complexity

According to Elliott [**51**] "everyone agrees that sustainable development is a good thing", however, to Fortune and Hughes **[52]** it is just a hollow concept without any practical constituent for an organization. Articulating such critiques may be attributed largely to the lack of appropriate and TBL inclusive data for analyzing and understanding the practical results of TBL-based systems [**1953**]. As mentioned previously, any TBL-based system involves a complex web of decision-making indicators and parameters [**54**]; therefore, an ideal set of data for such big and uncertain systems are not easily collectible. Hence, to collect an ideal set of data for modeling TBL-based systems; “the first question to be answered is not what do we want to measure? as one is often tempted to do, but rather, what question do we want to answer?”

(vi) Uncertainty

Due to the high level of uncertainty, sustainable development is a highly dynamic and hardly predictable concept [**55**]. This flexibility produces the variety of its interpretations and misconceptions. Additionally, due to the high level of uncertainty, the optimum point of any TBL-based system is not fixed and constantly moving [**56**] and it is, arguably, not predictable. Therefore, developing a simulation model for such phenomenon may require incremental change in modeling paradigms.

(vii) Morality and social norms

In essence, TBL-based systems are dealing with a set of normative factors carrying “ethical value level” goals. However, existing modeling methodologies are only capable of dealing with measuring indicators originated from practical and pragmatic levels [**57**]. Therefore, developing, implementing and validating such models, with the traditional modeling approaches seem prone to fail.

In summary, our research findings indicate a dearth 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.

4. An exploration of the TBL model in relation to 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 in M&S and (c) the limitations frequently associated with models found 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 abstractions 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 2** explores the comparative analysis of the viable and ideal TBL model criteria against capabilities of four frequently applied M&S techniques for sustainability purposes.

Table 2. Mapping the TBL system criteria with characteristic of modeling technique (Adopted from Zulkepli [**33]** and Brailsford, et al. [**58**])

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 [**58**, **59**];	Easy to learn and simple to model; It will be complicated if the system is big [**60**];	Developing and using the model for a big system is extremely complex [**61**];	Too complex to be applied and analyzed in managerial decision makings [**62**];
Assisting TBL-based decisions	High assistance, providing estimation, prediction, what-if-scenarios and cause & effect diagram [**63**];	High assistance, providing estimation, prediction and what-if-scenarios [**64**];	High assistance, providing estimation, prediction and detailed what-if-scenarios [**65**];	Medium assistance, proving estimation and prediction [**66**];
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 [**67**];	Efficient for microscopic view on the system; non-expert can understand how the system runs [**68**];	More efficient for representing both inside and outside of the system; non-experts may find it difficult to understand how the system runs [**64**]; 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 [**69**];
Dynamic Model	Provided as time included in the model; [**58**]; Provided as a result from any intervention that has been done to the model/system (what-if-scenarios) [**63**];	Provided as time included in the model [**70**];	Provided as time included in the model;	They are not essentially dynamic; Mostly used for mathematical optimization. A Monte Carlo simulation is time-stepped.

Criteria of a TBL model	System Dynamics (SD)	Discrete Event Simulation (DES)	Agent Based Simulation (ABS)	Mathematical Modeling (MM)
Dealing with different levels of abstraction in the system	Mostly dealing with high level of abstraction [**71**, **72**];	Mostly is using at low to middle level of abstraction [**72**, **73**];	Dealing with all abstraction levels [**74**];	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 [**75**, **76**].	May cover the whole system, but it will be complicated and complexity increases exponentially with size [**64**];	Can develop holistic models [**77**, **78**]. 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 [**79**];	Simplifying complexity for the process in the system, if system is too big, modelers tend to break down the system [**80**]. However, such approach cannot be applied for modeling the integrated TBL-based systems [**31**];	Simplifying the complexity of systems [**81**];	Simplifying complexity of systems;
Dealing with Data Complexity	Broadly drawn;	Numerical with some judgmental elements;	Dependent not only on data but also the interaction that is defined between agents;	Cannot easily deal with complex (mixed qualitative and quantitative) data;
Providing both Short- and Long-term decision making simultaneously	Compare with other three techniques, SD mainly uses at a higher, more aggregated and strategic [**78**];	DES is stochastic and mostly is being used at more operational or tactical level to answer specific questions [**33**];	Every well formulated SD model has an equivalent formulation as an ABS model. (Agency Theorem for System Dynamics) [**65**], However, while SD takes a top down strategic approach, ABS taking it as a bottom up approaches [**74**];	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 2**, when the single modeling approach was used, the capabilities of the techniques could not fully cater for all the needs and characteristics of the TBL-based system, thereby creating a gap between the system and the capabilities of the techniques. Section five discusses the gap between methods capabilities, TBL systems and viable TBL models. Section Six then presents suggestions on reducing this gap.

5. 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 4**). The conceptual representation is informed by our systematic study of literature in M&S for SOM. The bigger circle represents the ideal characteristics of TBL systems (these need to be modeled), the smaller circle represents the capabilities of current techniques to represent a TBL system. As can be seen from this figure, there is a gap between the characteristics that need to be modeled (outer circle) and those that can be modeled (inner circle). The gap may occur because no single simulation technique can adequately represent the characteristics of a TBL-based system (refer to **Table 2**). Because of this gap, it is arguable that the existing models developed using a single M&S technique are not ideal for decision making pertaining to TBL-systems. Arguably, the use of such models may 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 developed models 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 mixture 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 model more likely will take into consideration the overarching sustainability-related themes. **Figure 4** illustrates how such combined approach could reduce the gap in modeling the TBL-based system.

The gap between an ideal TBL-based model and the techniques depicted in **Figure 4** represent the capabilities that are offered by M&S techniques but which are not being used for the development of the model itself; the reason for this may be that there are some conditions inherent in the existing system that will not easily lend themselves to computer modeling (e.g. various normative and ethical level values involved in TBL-based systems). It is to be noted that such gap may exist for both single and hybrid techniques. The gap between modeling technique and TBL-based system may show that not all elements of the TBL-based system can be represented and/or modeled using M&S techniques. However, the use of hybrid simulation for model development 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 4**. The overlap between modeling technique one and two shows that the techniques have some common capabilities (See **Table 2**); 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 gap between which was highlighted above and ideally caters for all characteristics of underlying TBL-based systems.

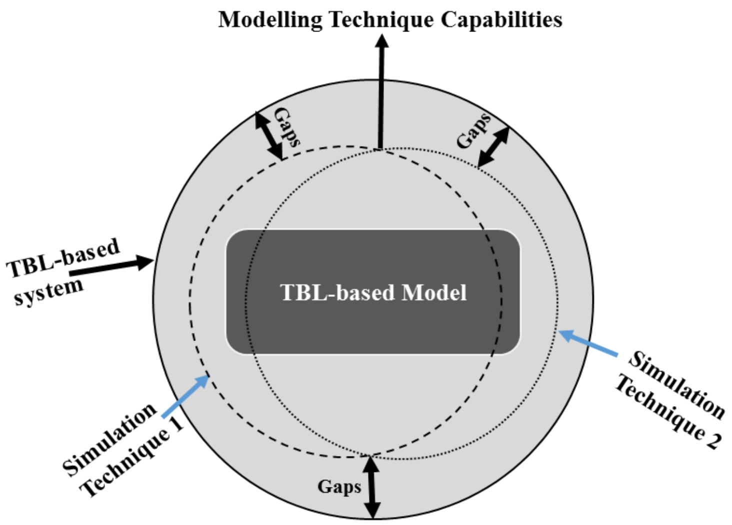

Figure 4. The gaps between system, model and technique
(Adopted from Zulkepli [**58**])

The complexity and uncertainty of TBL systems being modelled, together with the representation of multi-levels of abstraction (strategic and operational) as well as TBL multidisciplinary relationships may mean that combining OR/Simulation technique could enable the symbiotic relation of the strengths of individual techniques, while reducing their limitations, thereby potentially realizing synergies across techniques and facilitating greater insights to problem-solving **[33, 82].** According to Chahal and Eldabi [**83**], hybrid M&S is the deployment of multiple simulation techniques in an integrative way, where both approaches collegially and harmoniously improve each other's capabilities and mitigate limitations by sharing information. Hybrid approach could also aid stakeholder acceptance [**84**].

6. Discussion

The hybrid approach is not a new concept in M&S **[93].** It has been applied in studies where a single technique could not sufficiently represent the underlying complexities of the system [**58**, **84**]. The hybrid M&S approach has been conceptualized and/or implemented in many areas of business, such as manufacturing [**85**], transportation [**86**], maintenance operations [**87**], environmental disasters [**88**], as well as in healthcare systems [**89**, **90**]. In this research "TBL Hybrid Modeling" refers to the combined application of M&S techniques for modeling the TBL-based systems.

We have presented a discussion on the characteristics of a TBL model and have mapped this against the techniques. 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. This is also based on our investigation of the DES-SD hybrid approach for TBL modeling in healthcare [**31**]. 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. 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 thus 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 by our experience of the combined use of two discrete approaches ABS- DES [**91**] and SD-DES [**92**] 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 previously stated that hybrid M&S reduces the complexity, but developing a hybrid model can be very challenging [**70**]. So, as argued in this paper, 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 [**92**]. We have identified that there are two main challenges that have to be taken into the consideration while developing hybrid discrete-continuous model [**93**]. Firstly, a difficulty could be associated with the multiple representations of time which may occur due to combining static with dynamics systems in the TBL-based model. Secondly, it is also difficult to integrate a discrete, entity-level model with an aggregate level model (required in order to represent the multiple resolutions of the underlying TBL-based system).

As discussed earlier (section 3) the challenges of TBL modeling is not limited to hybridization. The difficulty of developing models for sustainability analysis is essentially related to the complexity and uncertainty of such system. Our findings show that such complexity appears from the early stages of the modeling exercise in the problem identification and conceptualization phase [**92**]. 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) [**94**]; this has been explained previously in section 3. 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.

7. 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. The paper presents a methodological review of literature in order to provide a synthesized view of M&S approaches which have been used to model sustainability issues in different industries. 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 encapsulate the requirements of a viable TBL model in isolation. In this paper, the main argument to support using hybrid simulation for TBL modeling is to analyze the TBL-based model at aggregate level for long-term (analyzing the system with low resolution) and at individual level for short-term period (analyzing the system with higher resolution) in order to present a model that is closer to the behavior of the real world TBL-based system. The assertion is that a combined simulation approach will provide a superior representation of the underlying behavior of the TBL system, compared with modeling the system using a single simulation technique. 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. To the best of authors' knowledge, there is no developed framework to provide guidance on how to develop TBL model using step-by-step instructions. As such, our future work involves the development of a generic multi-level hybrid M&S framework for sustainability analysis that could assist modelers to implement a reliable TBL model that neither ignores sustainable development dimensions nor misleads decision makers into making unsustainable decisions.

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