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MODELLING FOR SUSTAINABLE DEVELOPMENT USING THE TRIPLE-BOTTOM LINE: METHODS, CHALLENGES AND THE NEED FOR HYBRID M&S

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ABSTRACT

The concept of sustainable development (SDEV) is a topic of increasing significance in management decision making. SDEV is managed based on the triple-bottom line approach which stresses the importance of achieving a balance between economic, environmental and social impacts. In the context of management decision making, this implies that operational and strategic decisions in an organization must not be limited to the fulfillment of KPIs associated with productivity alone, but should also include metrics that are associated with the environment and society. Modeling & simulation (M&S) lends itself towards evaluation of the three, often competing, metrics. There are several M&S approaches like Discrete-event and System Dynamics; which of the existing techniques is the choice for modelling SDEV? Or, is a combined hybrid approach a better solution? The tutorial explores such questions related to the methodological aspects of M&S for SDEV analysis, and discusses the challenges for modeling such complex systems.

1 INTRODUCTION

Sustainable Development has been among the rapidly-growing research areas in recent years. Over the last three decades, the international community has been facing severe environmental and social challenges related to climate change and Corporate Social Responsibility. Findings show that such challenges are mostly the consequence of irresponsible activities at the corporate level (Welford 2013). It therefore comes as no surprise that during the past two decades there has been a significant increase of awareness of the need to reduce the impact of industrial activities that harm society and the environment (Reid 2013). Hence, organizations have realized that to respond effectively to these challenges, a shift in their management approaches is inevitable (Aschemann et al. 2012). Organizations are increasingly conscious of the fact that their continued success is dependent on achieving a balanced outlook of three main types of responsibility - namely, *Economic*, *Social* and *Environmental* - 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 SDEV 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, M&S could play a pivotal role in designing sustainability-related strategies since it allows the organizational stakeholders to 'experiment' prior to 'implementation' (Fakhimi 2016). Further, 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 numerous studies related to operations management and management science (Gunasekaran and Irani 2014) and there is a recognition of the 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). In our previous work we argued that research in SOM will benefit from the use of M&S approaches as they enable stakeholders to test various strategies in the TBL sphere (Fakhimi et al. 2013). Similarly, this will make a contribution to literature in M&S since several Key Performance Indicators (KPIs) could now be derived from the overarching SOM literature. How do we increase the adoption of M&S for TBL/SOM analysis? The approach we have taken in this tutorial paper is to dissect the concepts from SOM and the intricacies of TBL-based systems and looking at it through the lens of a modeler. By following this process, which included a review of literature, we identified what we consider to be six important characteristics of TBL-based systems that need to be considered by researchers and practitioners in the M&S community prior to developing a TBL model (see Table 1).

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

TBL Characteristics	**Description**
Vagueness and Ambiguity	A term is vague when it does not have a single specific and distinct definition (Zhang 1998). Despite the frequency associated with the invocation of the term vagueness, the concept of SDEV remains unexpectedly vague, indefinite, disputable, and has several variables that are hard to quantify (Azapagic 2003). During the period 1974–1992, for example, approximately 70 definitions appeared in the literature, with the number of studies devoted to the subject continually increasing (Moore 2011; Linsey 2010). Consequently, the fuzziness and irregularity in the SDEV concept have led to inconsistency and contradiction in choosing appropriate measuring indicators for analyzing SDEV.
Difficulty of Balancing TBL	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 (Keating 1993). Therefore, modeling for SDEV analysis would frequently involve numerous 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.
Trans-disciplinary	According to the McDonough and Braungart (2002) everything now is connected and nothing can be analyzed in isolation. Lang et al. (2012) also

	argue that SDEV 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 (Munda 2005). The further that SDEV 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.
Data Complexity	As mentioned previously, any TBL-based system involves a complex web of decision-making indicators and parameters (Bell and Morrse 2003); therefore, an ideal set of data for such big and uncertain systems is not easily collectible.
Uncertainty	Due to the high level of uncertainty, the optimum point of any TBL-based system is not fixed and is constantly moving (Bagheri and Hjroth 2007) and it is, arguably, not predictable.
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 (Newton 2003).

Jain et al. (2013) noted that the potential of M&S is yet to be fully explored in the area of TBL modelling. Existing literature suggests an unequal treatment of economic, social, and environmental factors among the SOM studies that employ qualitative models (e.g., conceptual models) and those using quantitative approaches like computer simulation (Fakhimi et al. 2016). While the former soft 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 the TBL framework and focused principally on the economy and the environment (e.g., studies on sustainable supply chain management, life cycle assessment).

Developing models that respond to complexities inherent in TBL-based systems is not a trivial task for modelers since they require to ensure that the developed artifacts are, (a) applicable to the real world, (b) consider the appropriate levels of details related to social, economic and environmental factors, and (c) consider all three SDEV pillars (TBL) in their analyses, together with productivity/efficiency-based criteria which may exist. M&S researchers and practitioners will therefore benefit from a more detailed look at the definitions, assumptions, conceptualizations and also implementation constraints associated with TBL modelling. It is with this objective that we have prepared our tutorial paper on modelling for sustainable development.

The remainder of this tutorial paper is organized as follows. The next section (Section two) introduces TBL modelling. Section three articulates the need for a shift in the M&S paradigm towards TBL modelling, and discusses the need for using hybrid simulation for SDEV analysis. Section four presents step-by-step guidelines for developing a TBL-based model using a hybrid simulation approach. Finally, Section five discusses the challenges and opportunities of TBL Modelling.

2 TBL MODELING AND EXPLORATION OF M&S TECHNIQUES

TBL-based systems can be complex and uncertain and they frequently incorporate both strategic and operational issues. 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 the productivity criterion (e.g., resource utilization, service time) but also on environmental and social criteria. Developing models to respond to such complexities require the specification, analysis and evaluation processes to be aligned with both the infrastructure and the surrounding subsystems of social valuation (here the three TBL component systems) and policy context. It may also necessitate a rethink on the methodological aspects of M&S techniques which lend to modeling of TBL-based systems.

It has been argued that SDEV in an organizational context is mainly a strategic concept (Gimenez et al. 2012). However, the realization of strategic and policy decisions is only possible through operational implementation, expressed initially through the establishment of policy. Taking an example from healthcare, SOM requires an understanding of the interplay of TBL (including political factors) at the strategic level; at the same time, it will also require an understanding of the operational elements of the system being modeled, for example, the pattern of patient arrivals and resource usage. The chosen modeling approach for SDEV analysis should ideally be able to represent, at appropriate levels of detail, both the operational and the strategic elements of the system being investigated in order to perform its function as a predictor of candidate policies in order to allow policy choices to be made.

From a systems perspective, it is important to take into consideration the effect on sustainability in both long-term and short-term; not least, because policy dilemmas will quite frequently emerge from their conflicting requirements. Long-term impacts arise mainly from strategic decisions; they are more holistic in nature (Chahal and Eldabi 2013). Processes with long-term effects should ideally be composed into an aggregate level of analysis in TBL modeling. On the other hand, short-term impacts generally are an outcome of operational-level decision making, although some decisions are conceived of as being strategic and therefore long-term, can also have immediate unexpected effects in the short term. Processes with short-term effects may be composed into an individual level of analysis in TBL modeling. However, our findings suggest that there are few studies (e.g. Ratan et al. 2010; Seuring and Muller 2008) that have used M&S in the context of SOM and that have taken into account the strategic and operational-level strategies that may be necessary for experimentation within a simulated environment and analysis prior to implementation.

As discussed earlier, due to the unique characteristics of SDEV, modelling such a complex phenomenon is not an easy task. Therefore, it is not surprising that we find several limitations/drawbacks in existing models found the literature. Table 2 indicates the list of limitations of the TBL-based models developed for the three most applied M&S techniques for sustainability analysis (Fakhimi et al. 2013).

Table 2: Limitations of the M&S techniques for modelling sustainability.

M&S Techniques	**Limitations for modelling the TBL-based systems**	**Example studies**
Discrete-event Simulation (DES)	- Does not cover the whole TBL-based system. - Tends to ignore the interconnections with high level and low level operations. - Does not support pro-active behaviour (which is important when simulating social factors of TBL). - Mostly used at operational level of abstraction rather than at strategic level.	Widok and Wohlgemuth (2011); Shao et. al. (2010); Jain and Kibira (2010); Fakhimi et al. (2015);
Agent-based Simulation (ABS)	- TBL-based model will be complex and difficult to completely understand. - Heavily dependent on data. - Developing model showing the details in high level resolution will be complicated and the size of model will be large.	Yang et al. (2011); Memari et al. (2011);
System Dynamics (SD)	- Complexity of finding interconnections between TBL agents that are not essentially homogenous. - More focus is on system rather than solving problems. - Tends to ignore the interconnections with high-level and low-level operations. - More efficient for representing outside of the system rather than the inside.	Shen et. al., (2005); Halog and Manik, (2011); Jain and Kibira (2010);

As summarized in Table 2, when the single modeling approach is used, the capabilities of any one specific technique cannot 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 three elucidates the need for hybrid simulation for TBL modelling, and then presents suggestions on reducing this gap. It will be seen later that this accommodation between multiple outputs is a distinguishing characteristic of the systems represented in both DES and SD as advocated and demonstrated in this work.

3 CHALLENGES IN SDEV MODELLING AND THE NEED FOR HYBRID M&S

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. We argue that the application of hybrid simulation lends itself to a closer representation of the TBL-system (when compared to using single techniques); A previous review by the authors (Fakhimi et al. 2016) found that indicates that DES-SD to be the preferred hybrid approach (Fakhimi et al. 2016). 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. Tako and Robinson 2009; Brailsford et al. 2010; Chahal and Eldabi 2013). Our work has built on existing research on technique selection and have applied this to TBL models. The purpose of Table 3 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. 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.

Table 3: Criteria for Selection between SD and DES for TBL modeling.

Criteria	DES	SD
Problem Perspective		
Purpose	Productivity based decisions: TBL optimization	TBL monitoring: strategic decision makings and learning
Problem Scope	Productivity related operations	Strategic
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		
Level of Resolution	Detailed individual level	Aggregate high level
TBL impact	Short-Term	Long-Term

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**.**

Despite the need for applying mixed discrete-continuous models for TBL modelling, there is a dearth of studies which has applied SD-DES in an integrated way. We argue that this could be due to, (1) lack of understanding about SDEV and TBL-based systems, and (2) the challenges associated with integrating M&S methods for analyzing such complex and uncertain systems. Thus, there is a need for an approach that provides step-by-step guidance on developing TBL-based models. Such an approach could aid in the development of models that are likely to be a better representation of the system under scrutiny. This is crucial for TBL modeling as the real system is complex and uncertain and different from traditional systems. The following section presents the description of our proposed approach.

4 USING HYBRID M&S FOR SDEV ANALYSIS

This section presents several phases, together with its rationale, that can potentially guide a modeler through the development of a TBL-based model. It is also useful for teaching TBL modeling, especially to novice modelers and those who are not familiar with the SDEV concept. This hybrid simulation approach entails three main phases. The composition of the phases is based on Brooks and Robinson's key stages of a simulation study (Brooks and Robinson 2000).

4.1 Phase I: Conceptualization of a TBL-model

The conceptualization phase aims to provide the modeler with a simplified conceptual model for a complex system, such as one that is TBL-based, in order to minimize the likelihood of incomplete, unclear, inconsistent and incorrect requirements. The first phase aims to guide the modelers to understand the problem, identify the general objective of the simulation study, and determine the scope, assumptions and content of the model.

The study starts with *problem and objectives identification*. This is to ensure the results of the TBL-based model are applicable to the real world. The challenge for identifying TBL problem initiates from knowing there is no single interpretation for the phenomenon of SDEV. Defining the cause of the problem in the system is challenging (Robinson 2010), especially when it addresses a wide range of different TBL related factors (e.g., energy cost, pollution, waste, employee satisfaction) and actors (e.g., public and private organizations, NGOs, international communities, individuals) involved, as they have varying (sometimes opposite) values, opinions and interests (Fakhimi et al. 2013). Unlike traditional discrete-event modeling where the focus was primarily on assessing productivity-related KPIs, problem identification in TBL modeling does not follow linear causal (command and control) principles (e.g. healthy food to prevent stomach-ache). Linear causal relation principle (Boudon 1965) "perceives tacitly that the problem is well bounded, clearly defined, relatively simple and linear with respect to cause and effect" (Holling and Meffe 1996). Hence, dealing with SDEV and TBL-based systems, linear and mechanistic thinking may mislead the modelers to see the complex, highly uncertain SDEV as engineered structures prone to management with predictable results.

Subsequent to the identification of the problem, a conceptual model should be developed in order to render more understandable the underlying TBL-based system. The challenge of conceptual modeling is to abstract an appropriate simplification of reality (Pidd 1999). A simplified conceptual model for a vague and complex system, such as a TBL-based system, could minimize the likelihood of incomplete, unclear and erroneous requirements (Robinson, 2008). Several approaches could be used in the development of a conceptual model, for example, SSM (Lehaney and Paul 1996; Kotiadis 2007) and QSD (Powell and Mustafee 2016).

Pidd (1996) argues that objective decomposition facilitates the method selection and model development for complex systems. Some of the existing M&S studies (i.e. Zulkepli 2012; Helal et al. 2007) propose using "modularization" for large systems rather than objective decomposition. We argue that modularization is not applicable to TBL modeling. Modularization originates from the software engineering field (Turban et al. 2007). The processes in TBL systems is too complex and interconnected; therefore, modularizing will be too difficult and potentially confusing. Furthermore, "the process of dividing a whole system into several modules depends on the size of systems of interests and the nature of the problem" (Zulkepli 2012). So, this would again be challenging for the large and all-inclusive TBL-based system. Moreover, TBL-based systems tend to have many stakeholders; therefore, modularization by creating many processes and sub-processes could be tedious and prone to inconsistencies (Fakhimi et al. 2014). We are proposing an objective decomposition approach to TBL modeling. This model decomposition will be based on the third principle of Pidd's (1996) conceptual modeling criteria. Finally, consideration must be given to the characteristics of SOM (Fakhimi et al. 2016). The system *should not* be divided to the TBL pillars (Environmental, Social and Economic) as three main objectives and then be integrated. Developing a conceptual model based on this misconception could lead to very misleading decisions. It is expected that by the end of this step, the model's boundaries will be identified by the modelers.

KPIs in TBL modeling should point to areas in the system, whereby the links between the economy, environment and society are weak and need to be addressed to achieve the overall modeling objective. The weakest link in the system that could be the root cause of the problem at hand referred as TBL-bottleneck. Subsequent to identification of the TBL KPIs, modelers define the TBL-bottleneck(s) of the system. In other words, TBL-bottleneck is that part of the system that could adversely impact in realizing/attaining sustainability of system under study. According to the United Nations Sustainable Development Report (2014) "indicators of SDEV need to be developed to provide solid basis for decision-making at all levels and to contribute to a self-regulatory sustainability of integrated environment and development systems". Therefore, modelers are required to ensure the exclusion of any TBL factors that are less likely have impacts on the underlying system as a result of the intervention. This will help the decision makers avoid being distracted by numerous TBL elements and factors. Identifying TBL Bottleneck and TBL KPIs will also help modelers define the scope of the model. This is a crucial step for reducing the complexity of dealing with TBL-based systems. Identifying the TBL-bottleneck and KPIs in this step should be followed by justifying the affected components in terms of why and how it affects the TBL-based model in the long-term and the short-term. This will help to analyze the impact of systems' intersections in relation to the TBL pillars (social, environmental and economic responsibilities) (further discussed in phase III; refer to sections 4.3).

4.2 Phase II: Design and Coding of TBL-based Models

The second phase starts with "Identifying the interaction formats in SD-DES hybrid simulation for TBL modelling". The external interaction format is the structure between TBL KPIs in two separate methods (SD-DES), while the internal interaction is that between KPIs within a common simulation method. Internal interaction in any hybrid simulation could be horizontal or vertical (Venkateswaran et al. 2005; Mallach 2000). Vertical integration refers to the interaction between different levels (operational and strategic) and horizontal integration refers to the interaction at the same level. On the other hand, external interactions in any hybrid simulation can be joined in three different formats: *"hierarchical format"*, *"process–environment format"* and *"process performance – environment format"* (Chahal 2010). Among the three hybrid interaction formats, *process performance - environment* is potentially a better fit. The central idea for this format for SDEV modelling is to understand the long-term impact of interventions in TBL KPIs on the sustainability of the whole system, for example, waiting time, energy usage, waste, and logistics etc. According to the literature, this format has been used to analyze the ripple effects of local operations from a broader perspective and used for "analyzing the continuity of operational interventions in the long run and evaluation of local actions from a global perspective (i.e. Umeda and Zhang 2008)". Therefore, this format arguably could help decision makers to show the long-term effect of their sustainable improvement initiatives from global perspectives. Unlike the hierarchical mode, DES is the leading model in this hybrid format. In this format, however, SD influences the entry gate (Chahal 2010), rather than internal activities and resources. Hence, application of *process performance-environment* could help modelers address the TBL modelling requirements.

TBL KPIs are then modelled by SD-DES and the interaction points are to be identified. According to Chahal (2010), the interaction points are actually the indicators that exchange information actively between the different techniques used for modelling. Accurate execution of the interaction points in the system will certify that the information exchange occurs between different components of the models. The aim of this step is to guide the modelers in their identification of the interaction points (What is exchanged?) between modelling techniques (SD and DES). According to the literature, there is a close relationship between interaction point and hybrid format (Gunal 2012). "Interaction points" in TBL models are TBL KPIs whose values are changed or influenced by TBL KPIs of the same model or another model during hybrid simulation. In TBL modelling, TBL bottleneck is playing a key role in identifying the interaction point.

Subsequent to the SD-DES interaction points having been defined, the next requirement is to identify the mode of interaction between SD and DES. As discussed above, formulating the interaction points in SD-DES hybrid modelling will help trace information exchange among the models. Identifying the mode of interaction facilitates understanding of how they interact in order to exchange accurate information. According to the literature, there are two modes of interaction in hybrid SD-DES modelling: (1) *cyclic mode*, and (2) *parallel mode* (Chahal and Eldabi 2013). They argue that in the *cyclic mode*, SD and DES interact when their individual running process is completed. In contrast, in *parallel mode*, SD and DES models run and interact simultaneously with each other. An appropriate mode of interaction for TBL-models should be implemented.

4.3 Phase III: TBL Analysis

In the third phase, we analyze the results using the TBL assessment framework. TBL is an assessment framework that guides organizations to harness their activities towards the attainment of sustainable success strategy. Harmonious synergies achieved through TBL can deliver a 'win-win' situation that realizes multiple interconnected aims (economic, social and environmental). Therefore, analyzing the results of TBL modeling requires an integrated approach to give balanced consideration to all three sustainability-related dimensions. However, the key issue is to allocate measurement scales and weights to TBL KPIs in order to select the most appropriate decision based on the simulation results.

Unlike traditional productivity-based models (i.e., models that focused mainly on KPIs related to resource utilization, efficiency, etc.), which are based on "Command-and Control" managerial disciplines, sustainability analysis requires becoming more integrated, flexible and resilient (Bagheri and Hjroth 2007). Measuring organizational performance is difficult, especially when what needs to be measured keeps changing. Hence, in order to analyze the results of TBL modeling, stakeholders need to be aware that the weights that may be assigned to individual components in the overarching TBL-assessment framework can change (balanced scorecards). The TBL-based model is responsible for monitoring the observing system against TBL framework and strategic priorities. Furthermore, the results require regular supervision to ensure: (a) all KPIs dealing with either of TBL pillars are within the established threshold; (b) decisions are made based on the short and long-term impact of KPIs on system performance. It goes without saying that short and long-term monitoring is static unless it links continuously to strategies and assessment of different futures (Holling 2001).

5 DISCUSSION AND CONCLUSION

The hybrid approach is not a new concept in M&S. It has been applied in studies where a single technique could not sufficiently represent the underlying complexities of the system. 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 challenges to 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 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.

REFERENCES

Aras, G., and D. Crowther. 2013. "Sustainable Practice: The Real Triple Bottom Line". *Developments in Corporate Governance and Responsibility* 5:1-18.

Azapagic, A. 2003. "Systems Approach to Corporate Sustainability: A General Management Framework". *Process Safety and Environmental Protection* 81(5):303-316.

Bagheri, A., and P. Hjorth. 2007. "Planning for Sustainable Development: A Paradigm Shift towards a Process based Approach". *Sustainable Development* 15(2):83-89.

Bell, S., and S. Morse. 2008. "Sustainability Indicators: Measuring the Immeasurable?" *Earthscan*. London, Sterling, Virginia, USA.

Boudon, R. 1965. "A Method of Linear Causal Analysis: Dependence Analysis". *American Sociological Review*, 365-374.

Brailsford, S. C., S. M. Desai, and J. Viana. 2010. "Towards the Holygrail: Combining System Dynamics and Discrete-Event Simulation in Healthcare". In *Proceedings of the 2010 Winter Simulation Conference*, edited by B. Johansson, S. Jain, J. Montoya-Torres, J. Hugan, and E. Yücesan, 2293-2303. Piscataway, New Jersey: IEEE.

Brooks, R. J., and S. Robinson. 2000. *Simulation Studies: Key Stages and Processes*. Hampshire, UK: Palgrave Macmillan.

Chahal, K. 2010. "A Generic Framework for Hybrid Simulation in Healthcare". School of Information Systems, Computing and Mathematics, Brunel University. PhD Thesis.

Chahal, K., T. Eldabi, and T. Young. 2013. "A Conceptual Framework for Hybrid System Dynamics and Discrete Event Simulation for Healthcare". *Journal of Enterprise Information Management 26*(1-2): 50-74.

Efraim, T., J. E. Aronson, T. Liang, and R. Sharda. 2007. *Decision Support and Business Intelligence Systems.* Upper Saddle River, New Jersey: Prentice-Hall.

Fakhimi, M. 2016. "A Generic Hybrid Modelling and Simulation Framework for Sustainable Development Analysis in Healthcare Context". Surrey Business School, University of Surrey. PhD Thesis.

Fakhimi, M., A. Anagnostou, S. J. E Taylor, and L. K. Stergioulas. 2014. "A Hybrid Agent-Based and Discrete-Event Simulation Approach for sustainable strategy planning and Simulation Analytics". In *Proceedings of the 2014 Winter Simulation Conference*, edited by A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, 1573-1584. Piscataway, New Jersey: IEEE.

Fakhimi, M., N. Mustafee, and L. K. Stergioulas. 2015. "An Investigation of Hybrid Simulation for Modeling Sustainability in Healthcare". In *Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, W. K. V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, 1585-1596. Piscataway, New Jersey: IEEE.

Fakhimi, M., N. Mustafee, and L. K. Stergioulas. 2016. "An Investigation into Modeling and Simulation Approaches for Sustainable Operations Management". *Simulation:Transactions of the SCS* 92(10):907-919.

Fakhimi, M., N. Mustafee, L. K. Stergioulas, and T. Eldabi. 2013. "A Review of Literature in Modelling Approaches for Sustainability". In *Proceedings of the 2013 Winter Simulation Conference*, edited by R. Pasupathy, S. H. Kim, A. Tolk, R. Hill, and M. E. Kuhl, 282-290. Piscataway, New Jersey: IEEE.

Gimenez, C., V. Sierra, and J. Rodon. 2012. "Sustainable Operations: Their Impact on the Triple Bottom Line". *International Journal of Production Economics* 140(1):149-159.

Gunal, M. M. 2012. "A Guide for Building Hospital Simulation Models". *Health Systems* 1(1):17-25.

Gunasekaran, A., and Z. Irani. 2014. "Sustainable Operations Management: Design, Modeling and Analysis". *Journal of the Operational Research Society* 65(6):801-805.

Halog, A., and Y. Manik. 2011. "Advancing Integrated Systems Modelling Framework for Life Cycle Sustainability Assessment". *Sustainability* 3(2):469-499.

Helal, M., L. Rabelo, J. Sepúlveda, and A. Jones. 2007. "A Methodology for Integrating and Synchronizing the System Dynamics and Discrete Event Simulation Paradigms". In *Proceedings of the 25th International Conference of the System Dynamics Society*, 3(3):1-24.

Holling, C. S. 2001. "Understanding the Complexity of Economic, Ecological, and Social Systems". *Ecosystems*, 4(5):390-405.

Holling, C. S., and G. K. Meffe. 1996. "On Command-and-Control, and the Pathology of Natural Resource Management". *Conservation Biology* 10:328-337.

Jahn, T., R. Aschemann, B. Sadler, M. Partidario, and R. Verheem. 2012. *Handbook of Strategic Environmental Assessment*. London, UK: Earthscan.

Jain, S., and D. Kibira. 2010. "A Framework for Multi-Resolution Modelling of Sustainable Manufacturing". In *Proceedings of the 2010 Winter Simulation Conference*, edited by B. Johansson, S. Jain, J. Montoya-Torres, J. Hugan, and E. Yücesan . 3423-3434. Piscataway, New Jersey: IEEE.

Jain, S., S. Sigurðardóttir, E. Lindskog, J. Andersson, A. Skoogh. and B. Johansson. 2013. "Multi-Resolution Modelling For Supply Chain Sustainability Analysis". In *Proceedings of the 2013 Winter Simulation Conference*, edited by R. Pasupathy, S.-H. Kim, A. Tolk, R. Hill, and M. E. Kuhl, 3318-3329. Piscataway, New Jersey: IEEE.

Keating, M. 1993. "The Earth Summit's Agenda for Change". Centre for Our Common Future: Geneva.

Kleindorfer, P. R., K. Singhal, and L. N. Wassenhove. 2005. "Sustainable Operations Management". *Production and Operations Management* 14(4):482-492.

Kotiadis, K. 2007. "Using Soft Systems Methodology to Determine the Simulation Study Objectives". *Journal of Simulation* 1:215–222.

Lang, D. J., A. Wiek, M. Bergmann, M. Stauffacher, P. Martens, P. Moll, M. Swilling, and C. J. Thomas. 2012. "Transdisciplinary Research in Sustainability Science: Practice, Principles, and Challenges". *Sustainability Science* 7(1):25–43.

Lehaney, B., and R. J. Paul. 1996. "The Use of Soft Systems Methodology in the Development of a Simulation of Out-Patients Services at Watford General Hospital". *Journal of the Operational Research Society* 47:864-870.

Lehaney, B., S. A. Clarke, and R. J. Paul. 1999. "A Case of an Intervention in an Outpatients Department." *Journal of the Operational Research Society* 50:877–891.

Linsey, T. 2010. "Sustainable Principles: Common Values for Achieving Sustainability". *Journal of Cleaner Production* 19:561–565.

Linton, J. D., R. Klassen, and V. Jayaraman. 2007. "Sustainable Supply Chains: An Introduction". *Journal of Operations Management* 25(6):1075–1082.

Mallach, E. G. 2000. Decision Support and Data Warehouse Systems. Singapore: McGraw Hill.

McDonough, W., and M. Braungart. 2002. *Remaking the Way We Make Things: Cradle to Cradle*. New York, USA: North Point Press.

Memari, A., B. W. Vom Berg, and J. M. Gomez. 2011. "An Agent-Based Framework for Adaptive Sustainable Transportation". In *Enabling Technologies: Infrastructure for Collaborative Enterprises (WETICE), 20th IEEE International Workshops*, 87-93. IEEE.

Moore, F. C. 2011. "Toppling the Tripod: Sustainable Development, Constructive Ambiguity, and the Environmental Challenge". *Consilience* 5:141–150.

Munda, G. 2005. "Multiple Criteria Decision Analysis and Sustainable Development". In *Multiple Criteria Decision Analysis: State of the Art Surveys*, 953–986. New York, US: Springer.

Newton, L. H. 2003. *Ethics and Sustainability: Sustainable Development and the Moral Life*. Upper Saddle River, NJ: Prentice Hall.

Pagell, M., and Z. Wu. 2009. "Building a More Complete Theory of Sustainable Supply Chain Management Using Case Studies of 10 Exemplars". *Journal of supply chain management* 45(2):37-56.

Patzelt, H., and D. A. Shepherd. 2011. "Recognizing Opportunities for Sustainable Development". *Entrepreneurship Theory and Practice* 35(4):631-652.

Pidd, M. 1996. "Five Simple Principle of Modelling". In *Proceedings of the 1996 Winter Simulation Conference*, edited by J. M. Cbarnes, D. J. Morrice, D. T. Brunner, and J. J. Swain, 721-728. Piscataway, New Jersey: IEEE.

Pidd, M. 1999. "Just Modeling Through: A Rough Guide to Modeling". *Interfaces* 29(2):118-132.

Powell, J. H., and N. Mustafee. 2016. "Widening Requirements Capture with Soft Methods: An Investigation of Hybrid M&S Studies in Healthcare". *Journal of the Operational Research Society* https://doi.org/10.1057/s41274-016-0147-6 (online first).

Ratan, S. R. A., A. Sekhari, M. Rahman, and A. A. Bouras. 2010. "Sustainable Supply Chain Management: State of the Art". *SKIMA*, 193.

Reid, D. 2013. *Sustainable Development: An Introductory Guide*. Routledge.

Robinson, S. 2008. "Conceptual Modelling for Simulation Part II: A Framework for Conceptual Modelling". *Journal of the Operational Research Society* 59(3):291-304.

Robinson, S. 2010. "Conceptual Modeling for Simulation". *Wiley Encyclopedia of Operations Research and Management Science*, Wiley, New York.

Seuring, S., and M. Müller. 2008. "From a Literature Review to a Conceptual Framework for Sustainable Supply Chain Management". *Journal of cleaner production* 16(15):1699-1710.

Shao, G., N. Bengtsson, and B. Johansson. 2010. "Interoperability for Simulation of Sustainable Manufacturing". In *Proceedings of the 2010 Winter Simulation Conference*, edited by B. Johansson, S. Jain, J. Montoya-Torres, J. Hugan, and E. Yücesan, 55-63. Piscataway, New Jersey: IEEE.

Shen, L. Y., Y. Z. Wu, E. H. W. Chan, and J. L. Hao. 2005. "Application of System Dynamics for Assessment of Sustainable Performance of Construction Projects". *Journal of Zhejiang University Science* A 6(4):339-349.

Tako, A. A. and S. Robinson. 2009. "Comparing Discrete-Event Simulation and System Dynamics: Users' Perceptions". *Journal of the Operational Research Society* 60(3):296-312.

Tang, C. S., and S. Zhou. 2012. "Research Advances in Environmentally and Socially Sustainable Operations". *European Journal of Operational Research* 223(3):585-594.

Umeda, S., and F. Zhang. 2008. "Hybrid Modeling Approach for Supply-Chain Simulation". *Lean Business Systems and Beyond*, 453-460. Springer, US.

United Nations (UN). 2014. "Prototype Global Sustainable Development Report". *RIO+20 United Nations Conference on Sustainable Development*.

Vat, K. H. 2004. "Conceiving a learning organization model for sustainable development: The IS manager's perspective based on soft systems methodology". In *Proceedings of Engineering Management Conference*, 2: 500-504, IEEE.

Venkateswaran, J., and Y. J. Son. 2005. "Hybrid System Dynamic-Discrete Event Simulation-Based Architecture for Hierarchical Production Planning". *International Journal of Production Research* 43(20):4397-4429.

Welford, R. 2013. *Hijacking Environmentalism: Corporate Responses to Sustainable Development*. Routledge.

White, L., and G. J. Lee. 2009. "Operational Research and Sustainable Development: Tackling the Social Dimension". *European Journal of Operational Research* 193(3):683–682.

Widok, A. H., V. Wohlgemuth, and B. Page. 2011. "Combining Sustainability Criteria with Discrete Event Simulation". In *Proceedings of the 2011 Winter Simulation Conference*, edited by ed. S. Jain, R.R. Creasey, J. Himmelspach, K.P. White, and M. Fu, 859-870. Piscataway, New Jersey: IEEE.

Yang, Q.Z., Y. Z. Sheng, and Z. Q. Shen. 2011. "Agent-Based Simulation of Economic Sustainability in Waste-to-Material Recovery". In *Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management*. Singapore, 1150–1154.

Zhang, Q. 1998. "Fuzziness-Vagueness-Generality-Ambiguity". *J Pragmatics*, 29(1):13–31.

Zhu, Q., J. Sarkis, and Y. Geng. 2005. "Green Supply Chain Management in China: Pressures, Practices and Performance". *International Journal of Operations & Production Management* 25(5):449-468.

Zulkepli, J. 2012. "A Theoretical Framework for Hybrid Simulation in Modelling Complex Patient Pathways". Brunel Business School, Brunel University. PhD Thesis.

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