Sustainability Analysis in Industry 4.0 Using Computer Modelling and Simulation

Masoud Fakhimi and Navonil Mustafee

Abstract Industry 4.0 proposes the use of digital and connected manufacturing technologies for enhanced value creation. The measures that are traditionally associated with value creation include the reduction in waste, increased productivity and efficiency improved profitability, etc. With a growing interest in sustainability, it is important to supplement the conventional definition of value-creation with factors related to the environment and the society. This inclusive definition could help the realisation of sustainable development. Computer simulation and modelling (M&S) could be valuable in providing the understandings and insights necessary for coping with such all-inclusive systems which have high levels of complexity. In addition, M&S could also provide immense opportunities for stakeholders to understand the underlying dynamics of industry 4.0's contribution to sustainable development targets. Although, the researchers have recently been applying M&S to plan and test industry 4.0 approaches but our findings show that using M&S for analysing the contribution of industry 4.0 on sustainable development are scarce. The outcome of this chapter provides insights toward future research directions and needs. Finally, this research argues for a shift from normal to post-normal M&S paradigms for sustainability analysis this is achieved through a discussion on normal and post-normal science concepts and assumptions.

Keywords Industry 4.0 · Modelling and simulation · Sustainable development · Triple bottom line

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1 Introduction

Industry 4.0 is known as Manufacturing 4.0 or the fourth industrial revolution. While the hallmarks of Industry 3.0 were the automation of individual machines and processes, Industry 4.0 promises not only the end-to-end digitisation of business processes and physical assets (vertical alignment) but also emphasises the integration of these digitised internal processes with that of their suppliers, customers and key value chain partners (horizontal alignment). Industry 4.0 is data-driven and is reliant on key technologies, including, standards for industrial engineering, automation and robotics, real-time data and acquisition through sensors/Internet-of-Things, high-speed networking, cloud computing, computational infrastructure to enable real-time analysis of high velocity -high volume data, business intelligence and real-time monitoring and predictions. However, the focus of this chapter is not on the technology or its promise of new business models, radical innovations or increasing efficiency, but instead, in understanding the implications of Industry 4.0 for sustainable development (SDEV) and the triple-bottom line (TBL) of sustainability. It enables us to identify underlying system-wide characteristics that contribute to achieving resilience through a balanced treatment of societal, environmental and economic factors.

Computer modelling and simulation (M&S) is widely used in the industry to develop future state models and to perform experiments by simulating candidate strategies. In the context of manufacturing and supply chains, computer models could be used for the identification and (ultimately) removal of bottlenecks, inventory management, waste reduction, logistics and supply chain network design. Similarly, such models can be used for planning an organisational transition from existing Industry 2.0/3.0 automation-levels to that necessitated by the fourth industrial revolution. Industry 4.0 models could be used for experimenting the impact of future automation and availability of real-time data in relation to horizontal and vertical integration, analysing the efficacy of existing logistic networks with simulated location updates (to mimic Radio-frequency identification (RFID) data), experimenting the impact on inventory levels with real-time data on sales (e.g., through Point of Sales terminals with retailers) made available by the supply chain echelons. We argue that, in the industry, the overwhelming majority of simulation models are developed from the perspective of the productivity optimisation and consequently the processes that are of interest are mostly related to business-specific functions with outcome variables/Key Performance Indicators (KPIs) often defining metrics related to efficiency, productivity, throughput, profitability, and so on so forth. Our previous work [1] has criticised such organisation-centric models as it fails to appreciate the interplay of the overarching environmental, social and economic factors (also referred to as the TBL of SDEV), within which an organisation operates (see Fig. 1). TBL is a framework that guides organisations to harness their strategies towards a balanced treatment of their social, environmental and economic responsibilities [2].

With Industry 4.0, end-to-end digital manufacturing technologies will lead to enhanced economic success; however, it is also vital to consider the environmental

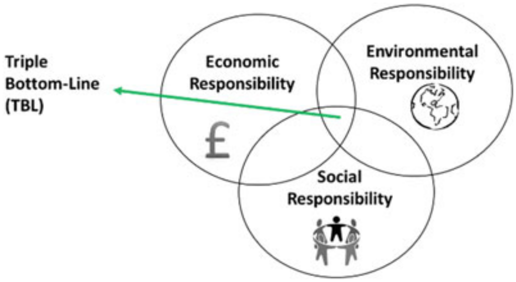

Fig. 1 The spheres of sustainable development

and social related KPIs to ensure organisations' sustainable success [3]. This book chapter extends our previous work on modelling approaches for sustainability analysis and applies this in the context of Industry 4.0.

2 Sustainable Development and Industry 4.0

The "Brundtland Commission" defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [4]. In recent years, the concept of "sustainability" has gained increasing attention in organisational and managerial disciplines. Such shifts in organisational paradigms placed demands on stakeholders to revise their priorities from productivity focused management to TBL [5]. Therefore sustainable manufacturing has emerged as an evolving field and has been the focus of numerous studies in operations management and sustainable development research communities [6]. Sustainable manufacturing can be defined as the planning, coordination, and control of a system that adds value to the stakeholders through the most cost-effective approach while striving to protect the environment and respecting social norms and responsibilities [7]. Linton et al. [8] argue that, in essence, the implementation of sustainable development requires a major shift in current conventional managerial disciplines and practices.

In organisations that implement Industry 4.0 technologies, real time access to data and information play a significant role in ensuring quick decision making. This also contributes towards cost savings. The use of real time data could also provide manufacturers with more accurate demand forecasts which lead to an increase in the resource utilisation and waste reduction [9]. The also numerous possibilities to analyse and improve sustainable manufacturing using the Industry 4.0 capabilities. For example, the use of IoT changes the sustainable operations management paradigms and provides manufacturers with the privilege of data source to "trace, extract and influence" the processes related to either of TBL (such as energy use and pollution) or material flows.

In summary, Industry 4.0 is transforming businesses by creating more efficient manufacturing methods, optimised supply chain and life cycle traceability and information management. In this new setting, with plentiful opportunities arising for manufacturers, the question is how it can contribute to the implementation of organisations' sustainable development strategies against TBL framework.

We argue that M&S could provide a valuable tool for analysing sustainable manufacturing strategies within the industry 4.0 setting. However, our findings show that most of the existing research on sustainable manufacturing led by Industry 4.0 relates to literature reviews e.g., [10, 11] with only a small number of empirical research having been reported e.g., [12–14]. There are limited number of studies which have explained the application of M&S for Industry 4.0 for SDEV analysis i.e. [15, 16]. The next section discusses the application of M&S for sustainability analysis in Industry 4.0 setting and how industry 4.0 capabilities could help the modellers to tackle some of the challenges of developing models for sustainability analysis.

The remainder of this chapter is organized as follows. The next section provides an overview on application of M&S for TBL modelling using Industry 4.0. Section three articulates a need to shift from normal to post normal modelling for sustainable development analysis. Section four is the concluding section and summarises the chapter.

3 TBL Modelling and Industry 4.0

3.1 Overview of Application of M&S for Sustainable Development Analysis

Tackling issues related to Sustainable Development (SDEV) has become increasingly crucial for organisational success. The initial pragmatic solution is to incorporate TBL criteria for any decision making process across the organisation. Over the last two decades, research in sustainable operations management (SOM) has made significant contribution towards the understanding and implementation of TBL in manufacturing. Modelling and Simulation is a frequently applied decision-making technique for representing and analysing complex systems. Hence, TBL-based systems, being complex, uncertain and having multiple system outputs, could leverage the abilities of M&S techniques to capture multiple perspectives and the effect of quantifiable and non-quantifiable TBL metrics for analysing systems.

In previous work we have shown that M&S allows for the experimentation of alternate TBL-centric strategies and to compare the results of the simulation in a meaningful way. M&S studies have been widely used in industry to gain insights into existing or proposed systems of interest. However, our review of the literature [1] shows the dearth of empirical research on integrating sustainability factors with systems' modelling studies. It is with this aim of addressing this gap that we have conducted a review of literature which attempts to provide a synthesised view of M&S approaches which have previously been used to model sustainable development issues. Note that this study was not specific to Industry 4.0 but included studies that focussed on both SDEV and M&S. As several of the studies identified in the review were to do with manufacturing, we consider it important to summarise the findings from this paper as it is of relevance to Industry 4.0 manufacturing.

Our study [1] found that system dynamics (SD), mathematical modelling (MM), discrete-event simulation (DES) and agent-based simulation (ABS) were the most widely applied techniques addressing sustainable development related issues. Every technique has a methodological foundation, for example, SD adopts a holistic systems perspective and uses stocks, flows and feedback loops to study the behaviour of complex systems over time; ABS takes a bottom-up approach to modelling wherein the overall behaviour of the system emerges from the underlying dynamic interaction between the agents; DES is used to model queuing systems [17]. Finally, MM uses mathematical notations and relationships between variables to model the behaviour 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 behaviour, 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 modelling particular classes of SDEV's problems.

Our findings also reveal that despite the recent endeavours to apply M&S for sustainability analysis, in many cases at least one of the pillars of the TBL framework (Economy, Society and Environment) has been neglected. Most empirical studies focused on economy-related measures to evaluate system performance and consideration of all three sustainability dimensions (TBL) has been underrepresented. This shows that existing studies have continued to ignore the interconnected impact of the TBL pillars on the success of short term and long term productivity. This excessive focus on productivity may need to change, since the decisions being made based on such models would not be aligned with the discipline of sustainable development discipline, but also can be very misleading for the whole organisation.

The recent increase in the number of publications in this area notwithstanding, our findings have shown that there is a lack of studies on the application of M&S for sustainable manufacturing incorporating all TBL factors of underlying systems, and many challenges still remain unaddressed in developing and validating such models. The development of models that respond to these TBL-based systems complexities is a particularly arduous task for modellers, since they require to ensure that the models are: (a) applicable to the real world, (b) capable of dealing with variables at different levels (strategic level and operational level), (c) considering all three sustainability pillars (TBL) in their analysis, and (d) capable of dealing with high level of uncertainty and complexity. Therefore, it is not surprising that a variety of limitations and drawbacks of the models was found in this literature review. Table 1 indicates the list of limitations exhibited by the TBL-based models that were developed for the studies reviewed for this research. The limitations found in the literature have been classified based on the simulation techniques they used.

Our findings advocate that a combination of M&S techniques (Hybrid Simulation) lends itself to a closer representation of the TBL-system (when compared to using single techniques). Our previous work shows that DES-SD [27] and ABS-SD [28]

Table 1 Limitations of the developed models addressing the sustainability issues

M&S techniques	Limitations for modelling the TBL-based systems	Example studies
System Dynamics (SD)	– Complexity of finding interconnections between TBL KPIs that are not essentially homogenous – More focus is on system rather than solving problems – More efficient for representing outside of the system rather than the inside	i.e. Shen et al. [18], Halog and Manik [19], Jain and Kibira [20]
Mathematical Modelling (MM)	– It is hard to quantify immeasurable TBL KPIs (i.e. social responsibility related KPIs) – Lack of feedback analysis in implementing TBL intervention – Tends to ignore the interconnections with high level and low level operations – Hardly capable of covering the whole TBL-based system	i.e. Sander et al. [21], Hashmi et al. [22]
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 proactive behaviour (which is important when simulating social factors of TBL) – Mostly used at operational level of abstraction rather than at strategic level	i.e. Widok and Wohlgemuth [23], Shao et al. [24], Jain and Kibira [20]
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	i.e. Yang, et al. [25], Memari et al. [26]

to be the preferred hybrid approach for TBL modelling as they could model most underlying characteristics of TBL-based system.

3.2 Application of M&S for TBL Modelling for Industry 4.0 SDEV Analysis

M&S has been used for SDEV analysis in most major industries such as Healthcare i.e. [29, 30], Manufacturing i.e. [31, 32], Food and Agriculture i.e. [33, 34], Construction Industry i.e. [35, 36], Transportation i.e. [37, 38], and etc. It is arguable that sustainable Industry 4.0 could also benefit from the use of M&S. However, as noted by Rodic [39] the potential of M&S is yet to be fully exploited in this new industry.

We define a TBL-based model as an abstraction of an underlying system of interest that is developed to analyse the system pertaining not only to the productivity criterion (e.g., resource utilization, service time) but also on environmental and social criteria. The development of suitable models is response to such complexity is reliant on aligning the specification, analysis and evaluation processes, the infrastructure and the surrounding subsystems of social valuation (here the three TBL component systems) and policy context. Moreover, reconsideration of the methodological aspects of M&S techniques is essential in relation to the development of TBL-based systems.

It has become necessary for manufacturers to abandon traditional design practices in favour of a systems-design approach as a result of shortened product development cycles and the negative impact on TBL. However, this has been difficult to achieve without the elements offered by Industry 4.0. During the initial development stages of TBL models, manufacturers are able to authenticate the design alongside TBL targets. An automated operation can considerably facilitate and ease the development of models for complex and uncertain systems [40, 41]. By modifying the structure of a model, TBL-based improvements can be made by creating multiple versions of the model and input data, alongside a comparison of the simulation outcomes. Algorithms can be devised to construct or adjust simulation models in relation to the input data; thereby speeding up the process of developing the TBL-based model. This is particularly pertinent to TBL-based models where the simulations are dealing with large and complex systems holding several immeasurable variables. However, automation demands modification of the model composition using an algorithm that has no manual intervention [42].

Furthermore, within an organisational context, SDEV arguably is a primarily strategic concept [43]. Nevertheless, decision pertaining to strategy or policy can be realised only through their implementation at an operational level. For example, in Industry 4.0, a modeller must comprehend the strategic interaction of TBL while simultaneously being sympathetic towards the operational aspects of the system. Ideally, the method selected to conduct SDEV analysis should epitomise, at appropriate levels of detail, the strategic and operational elements of the system under investigation. This will ensure it can predict candidate policies; thereby facilitating a choice of policy.

Moreover, it is vital to contemplate the short and long-term impact sustainability for analysing TBL-based systems because policy dilemmas will quite frequently emerge from their conflicting requirements. In the long-term, the impact will come primarily from strategic decisions, which are, by nature, more holistic [44]. Processes with long-term effects should ideally be composed into an aggregate level of analysis in TBL modelling. Conversely, the short-term effects arise generally from decisions made at the operational level, 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 modelling. Nevertheless, our findings suggest that there are few studies that have used M&S in the context of sustainable Industry 4.0 and that have taken into account the strategic and operational-level strategies that may be necessary for experimentation within a simulated environment and analysis before implementation occurs.

It has been argued by some critics that sustainability cannot be modelled due to its size, complexity, ambiguity and the fact that no adequate definition has been provided [45]. However, we argue that combination of Digital Twin and Virtual Testbeds promoted by industry 4.0 [46] extends the use of simulation modelling for TBL modelling in manufacturing especially with regards to TBL-based Product lifecycle management (PLCM). "Digital Twins" refers to the virtual substitutes for real objects consisting of virtual representations and communication capabilities comprising smart objects that act as intelligent nodes within the internet of things [47]. Integrating real-world data with the simulation yields precise predictions of relating to productivity or maintenance alongside green and social influences of products across its lifecycle based on the circulation of real-world data. When Virtual Testbeds and Digital Twins are combined, a new type of dynamic and experimental Digital Twin is created, which is ground-breaking in the simulation of large and complex systems [47]. The real value of Digital Twins lies in their ability to be tested extensively beyond the scope of the real world [39, 48]. Moreover, Digital Twins is a trusted system in a field where automated systems change continuously as it can offer a reliable analytics sandbox where the "what-if" scenarios can be analysed and experimented with low cost and complexity. Therefore, the TBL-based model could represent the operation of the system using real-time (or near real-time) data, or thereabouts, yielded from the TBL-based system. Furthermore, this will enable the modeller to analyse the system with high and low resolution by clicking on model objects and excavate a broad range of economic, environmental and social data, and perform an operational and holistic analysis.

In summary, Industry 4.0 application could help the modellers to tackle some of the challenges of TBL modelling which can hardly be resolved in traditional industries:

(1) Industry 4.0 can help the modellers and decision makers to understand, analyse the integration of all TBL measurable success factors within the system.

(2) In TBL modelling the modellers should be able to represent and analyse the system at high and low level of resolution. Industry 4.0 facilitates representation of more aspects and details of the underlying TBL-based model at different level.
(3) Industry 4.0 also could automate the modification (testing what-if questions) thanks to its reliable and real-life (or close to real life) data and analytics sandbox.

Notwithstanding the several benefits that Industry 4.0 could offer to TBL modelling, this research argues that due to the unique characteristics of Sustainable Development, TBL modelling still may require major re-thinking on traditional M&S disciplines. The next section argues for a shift from normal to post-normal M&S paradigms for sustainability analysis; this will be achieved through a discussion on normal and post-normal science concepts and assumptions.

4 From Normal to Post Normal Modelling for Industry 4.0 Sustainability Analysis

On the basis of the knowledge gained from the literature and limitations of existing empirical studies on TBL modelling, this research argues for a shift from normal to post normal modelling for Industry 4.0 sustainability analysis. We argue that modelling for sustainability based on classical science disciplines is not feasible to understand a phenomenon like Sustainable Development. The rest of this section explains this argument. We will further discuss why modelling for sustainability may become a Holy Grail for modellers.

The normal (classical) science is dominated by the concepts emerging from equilibria and optimality; thus, perception and treatment of changes for scientists are rather easy to formulate and predict. According to the principle of distinction conservation [49], "Classical science initiates with making as precise as possible distinction between the different components, properties and states of the system under observation". Normal science is grounded in the Newtonian worldview (reductionism concept), which implies that to understand any complex phenomenon, you need to take it apart [50]. Newtonian reductionism idea advocates that mathematical models are reducing the elements of system variables to a "machine" to represent the observing system in a set of differential equations [49, 51]. Bagheri and Hjorth [52] argues that normal science is mainly based on Equilibrium and Optimality. Meaning there is only one rigid solution for all differential equations and there is only one optimum point for a system. Due to these reasons, the logic behind it is not valid for open systems, which include unpredictable, uncertain and sometimes idealistic factors that do not have a unique final state as "optimum or minimum". Moreover, using a reductionism view for studying complex systems coping with unpredictable and immeasurable factors (human, environment, etc.) factors which naturally cannot be studied separately and do not obey mechanistic laws, is not practically possible. This explains the reason why normal science ignores all issues related to social and ethical values. Clark et al. [53] argue that since traditional mathematical (quantitative) systems are only capable of functioning but not of evolving. So they are not capable of coping with structural changes in open system. Thus, dealing with such open systems' shift to a post-normal mode is a critical change [54].

Post-Normal Science (PSN) was initially established to critique the Newtonian reductionism world view, which eliminates some uncertainties and social values associated to the observing system [55, 56]. PNS is a problem-solving framework developed by Silvio Funtowicz and Jerome Ravetz in 1990 [57] in order to study the underrepresented parts, the management of complex science-related issues. Funtowicz and Ravetz developed an argument claiming that the sciences tackling sustainability issues are profoundly different from those sciences that are involved in generating them (such as the applications of physics and molecular biology [58]. Bagheri and Hjorth [52] argue that classical science is all about treating the "symptoms", but the post-normal science is exclusively concerned with treating the "cause".

Therefore, we argue that, the most important factor for low adoption of M&S for sustainability analysis in Industry 4.0 is the fact that M&S methodologies are mainly applying mechanical concepts relying on equilibria and optimality, while TBL-based systems entail constantly moving processes where the optimal point is not known in advance; therefore using traditional M&S disciplines is less likely to be useful when analysing sustainability in Industry 4.0 systems, which are governed by large numbers of immeasurable factors that do not necessarily obey such disciplines. Therefore, the challenges and complexity of TBL modelling arguably are due to modellers trying to deal with these issues using normal science disciplines; it is like measuring length using scales.

5 Summary

M&S tools are one of the key element for the development of Industry 4.0. M&S play a significant role for modernising processes and designs as well as piloting and testing new products or services. Sustainable manufacturing principles used in tandem with M&S techniques could provide significant insights in coping with the uncertainty associated with TBL management. However, the application of M&S for analysing SDEV in Industry 4.0 is still at its infancy. According to the findings of this research, the most important factor for low adoption of M&S for industry 4.0 sustainability analysis is the fact that M&S methodologies are mainly applying mechanical concepts relying on equilibria and optimality, while sustainability systems entail constantly moving processes where the optimum point is not known in advance; therefore using traditional M&S disciplines less likely to be useful when observing sustainable systems entails a large number of immeasurable factors that do not necessarily obey such disciplines. This research presented a review of M&S and recent developments on applying M&S for sustainability purposes. The aim of this research was to investigate the challenges in developing models for sustainability analysis in Industry 4.0. Understanding and tackling these challenges provides immense opportunities for the realisation of sustainable development in using M&S

in industry 4.0. This research also showcased the opportunities which Industry 4.0 offers to TBL modelling.

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