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Simulation modelling for sustainability: a review of the literature

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ABSTRACT

This article is a review of work published in various journals and conference proceedings on the topics of Simulation Modelling for Sustainability between January 2000 and May 2015. A total of 192 papers are reviewed. The article intends to serve three goals. First, it will be useful to researchers who wish to know what kinds of questions have been raised and how they have been addressed in the areas of simulation modelling for sustainability. Second, the article will be a useful resource for searching research topics. Third, it will serve as a comprehensive bibliography of the papers published during the period. The literature is analysed for application areas, simulation methods and dimensions of the triple bottom line model of sustainable development.

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Sustainability; simulation; modelling; literature review; sustainable development

1. Introduction

Sustainability is the capacity to preserve, endure and nurture. It means identifying, developing and promoting sustainable mindsets, practices and policies in order to maintain a healthy natural environment but in an economically sound as well as socially viable manner.

However, assessing a particular activity's contribution to sustainability is difficult for a number of reasons. First, the concept of sustainability is vast in scope both temporally and geographically. Consequences of certain decisions in sustainability demonstrate over a long time and geographically away from their origins. Study questions may range over hundreds or even thousands years; and may cover over villages, regions, countries or even the whole earth. Second, the level of complexity in study questions can be very high not only because of the vast scope to deal with, but also because of multiple interactions to consider among economic, environmental and social elements. Third, interactions among critical components in question are often dynamic, non-monotonic and non-deterministic. Fourth, systems in question often do not exist yet. But it may be necessary to investigate the impact of various scenarios or different plans on sustainability before actual implementation. Fifth, different levels of granularity may have to be handled at the same time. For example, it may be necessary to model traceable connections between activities of individual human being and their ultimate effects on the earth.

These problems can be handled better by simulation modelling than any other available methods. Simulation is a kind of modelling, but refers to a group of methods that imitate the behaviours and characteristics of real systems, normally on a computer. Typical uses of simulation are (i) to develop a better understanding and gain insights of a system, (ii) to compare various plans and scenarios before implementation, (iii) to predict behaviours of a system, (iv) to aid decision-making processes, (v) to develop new tools for investigation and (vi) for training.

There are numerous methods of simulation available. However, three major ones, which are only considered in this article, are Agent-Based Modelling and Simulation (ABMS) (Gilbert 2008), Discrete-Event Modelling and Simulation (DEMS) (Law 2014), and System Dynamics Modelling and Simulation (SDMS) (Sterman 2000).

ABMS is a simulation method in which agents are modelled to interact with each other and their environment. Emerging behaviours, patterns and structures from such interactions over time are results used for various purposes. Each agent is an individual entity possessing its own intelligence, memory and rules. Agents make decisions based on what they perceive from other agents and their environment. The basic idea of ABMS is to model complex systems adopting a bottom-up approach starting from individual agents.

DEMS derives its name from the basic mechanism that a system's state variables change only at discrete and separate points in time. Events occur in those points in time and they are the only instances where the state of the system changes. DEMS typically models a complex system as an ordered sequence of events, even though complicated sequences and hierarchical structures can be employed. Uncertainties associated with events can be modelled explicitly and their collective consequences in the system are analysed statistically.

SDMS is a type of continuous simulation where a system's state variables change continuously over time. Commonly, differential equations are used to represent such continuous changes in state variables. Conceptually SDMS models a complex system

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incorporating three elements: (i) a stock that is a reservoir for a resource, (ii) a flow that adjusts the level of stock through in-bound flows and out-bound flows and (iii) a link between a stock and a flow. In contrast to ABMS, SDMS adopts a top-down approach, conceptualising a complex system at a more aggregate level.

This article presents a review of the literature on simulation modelling for sustainability, published between 2000 and 2015 (31 May). The article intends to serve three goals. First, it will be useful to researchers who wish to know what kinds of questions have been raised and how they have been addressed in the areas of simulation modelling for sustainability. Second, the article will be a useful resource for searching research topics. Third, it will serve as a comprehensive bibliography of the papers published during the period. Readers are expected to have fundamentals of sustainability and other well-established approaches to sustainability. Therefore, such foundational articles are not reviewed in this article. Instead, general references are provided in the reference list (Elkington 1994; Hardin 1968; Huijbregts et al. 2008; de Kerk and Manuel 2008; Kouloumpis, Kouikoglou, and Phillis 2008; Meadows et al. 1972; Siche et al. 2008; UNGA 1987; Wolfslehner and Vacik 2008).

This article is divided into six sections. How papers were selected for review and organised is explained in Section 2. Critical evaluation of uses of the simulation methods for sustainability is presented in Section 3. Section 4 provides synopses of papers in each application area. Analysis of data tagged from the reviewed papers is presented in Section 5. The article concludes in Section 6 with observations, trends and limitations.

2. Methodology

Papers reviewed in this article had been selected as follows. First, the period to be covered was decided. Then, two primary scholarly search engines were selected: 'Scopus' and 'Google Scholar'. Two key terms, 'sustainab*' and 'simulat*' were used to search papers in the two search engines. From the list resulted from Scopus, the first 2000 papers were examined individually for their relevancy for this article's objective. From the list resulted from Google Scholar, also the first 2000 papers were examined individually for their adequacy. Particularly, special attention has been paid to detect papers merely using the word 'sustainable' but meaning differently. From the list of initially qualified papers, the predominant presence of three journals and one conference's proceedings was noticed. They were 'Journal of Cleaner Production', 'Journal of Industrial Ecology', 'Environmental Modeling & Software' and 'Winter Simulation Conference Proceedings'. Therefore, all the issues from these four sources had been examined and additionally found papers were added to the list. At this stage, the result yielded over 300 papers published over 150 journals and conference proceedings.

It was further decided to restrict the review only to the papers that explicitly adopted one of three main simulation methods:

(1) Agent-Based Modelling and Simulation (ABMS),
(2) Discrete-Event Modelling and Simulation (DEMS),
(3) System Dynamics Modelling and Simulation (SDMS).

Finally, a total of 192 papers were identified for the review in this article. Out of the 192 papers, 11 of them are generic in nature and not particularly tied with any of the three methods.

A classification scheme was developed based on the contents of the surveyed papers. Application areas of the papers were the main criteria for setting up the classification scheme and ultimately a total of 18 categories were established. When a paper dealt with more than one application area, an area that the paper weighed most was selected. The categories are: (1) Agriculture, Aquaculture & Livestock, (2) Construction, (3) Ecosystem & Climate, (4) Energy, (5) Human Health, (6) Information Systems, (7) Land Use, (8) Manufacturing, (9) Mining, (10) Overview & Review, (11) Social Behaviour, (12) Supply Chain, (13) Sustainable Development, (14) Tourism, (15) Transportation, (16) Urban & Community Planning, (17) Waste, Recycling & Reuse, and (18) Water Resources. The categories and corresponding papers classified to each of them are presented in Table 1.

Two additional classification schemes are included in this article. One is according to dimensions of the triple bottom line model (Elkington 1994) of sustainable development (UNGA 1987) – environmental, economic and social; and the other is according to methods of simulation – ABMS, DEMS and SDMS. The triple bottom line model extends the traditional performance measurement by incorporating social and environmental factors in addition to financial factor. More detailed analyses on these classification schemes are presented in Section 5.

3. Critical evaluation of uses of simulation modelling for sustainability

Reviewing the selected papers brought up numerous contributions that the simulation modelling made to advance sustainability science, but it also revealed some shortcomings of the simulation modelling approaches for sustainability investigations.

3.1. Contributions of simulation modelling to sustainability science

3.1.1. Exploring various scenarios/strategies/policies

Many study questions involve constructing different scenarios (also strategies or policies) that researchers wish to experiment in order to understand eventual effects on sustainability (Aslani, Helo, and Naaranoja 2014; Aubert, Muller, and Ralihalizara 2015; Balbi, Bhandari, et al. 2013; Balbi, Giupponi, et al. 2013; BenDor, Scheffran, and Hannon 2009; Berman et al. 2004; van Beukering and Janssen 2001; DeLaurentis and Ayyalasomayajula 2009; Dong et al. 2012; Erdmann and Hilty 2010; Hong et al. 2011; Jager, Schmidt, and Karl 2009; Lovrić, Li, and Vervest 2013; Lyons and Duggan 2015; Martins et al. 2014; Nikolaou, Evangelinos, and Filho 2015; Rebaudo and Dangles 2013). Simulation modelling provides various means to systematically, objectively and quantitatively explore such scenarios, then compare their consequences. Typically, researchers establish and construct a valid baseline scenario, then are able to extend the simulation model to inquire into different scenarios. Also simulation modelling has been used to discover new scenarios or policies to explore (Gerst et al. 2013).

Table 1. Application areas and corresponding papers.

Application areas	References
Agriculture, aquaculture & livestock	Balbi, Bhandari, et al. (2013); Belcher, Boehm, and Fulton (2004); BenDor, Scheffran, and Hannon (2009); Iwamura et al. (2014); de Kok, Engelen, and Maes (2015); Li, Dong, and Li (2012); Martins et al. (2014); Rebaudo and Dangles (2013); Saysel, Barlas, and Yenigün (2002); Schouten, Verwaart, and Heijman (2014); and Schreinemachers and Berger (2011)
Construction	Ahn et al. (2009); Ahn et al. (2010); Gonzalez and Echaveguren (2012); Hong et al. (2011); Li and Lei (2010); Mallick et al. (2014); Pearce, Bernhardt, and Garvin (2010); Zhang (2015); and Zhang et al. (2014)
Ecosystem & climate	Aubert, Muller, and Ralihalizara (2015); Belem et al. (2011); Gerst et al. (2013); Learmonth et al. (2011); Machado et al. (2015); Mizuta and Yamagata (2001); Munthali and Murayama (2014); Polhill, Gimona, and Gotts (2013); Rogers et al. (2012); and Schreinemachers, Berger, and Aune (2007)
Energy	Aslani, Helo, and Naaranoja (2014); Barisa et al. (2015); Batten (2009); Blumberga et al. (2014); Colson et al. (2014); Davis, Nikolic, and Dijkema (2009); Franco, Castaneda, and Dyner (2015); Hollmann (2006); Jager, Schmidt, and Karl (2009); Kiesling et al. (2009); Miller et al. (2012); Qudrat-Ullah (2013); Ramchurn et al. (2011); Reddi et al. (2013); Robalino-Lopez, Mena-Nieto, and Garcia-Ramos (2014); and Shih and Tseng (2014)
Human health	Alexopoulos et al. (2001); Brailsford, Desai, and Viana (2010); Djanatliev and German (2013); Fakhimi et al. (2014); Kumar and Kumar (2014); Lin et al. (2013); Lyons and Duggan (2015); McKnight and Finkel (2013); Petering et al. (2015); and Viana (2014)
Information systems	Erdmann and Hilty (2010); Hilty et al. (2006); Lovrić, Li, and Vervest (2013); and Sissa (2012)
Land use	Barnaud et al. (2013); Bert et al. (2011); Caillault et al. (2013); Chen, Chang, and Chen (2014); Filatova, Voinov, and van der Veen (2011); Le, Seidl, and Scholz (2012); Miyasaka et al. (2012); Murray-Rust et al. (2014); Parker et al. (2003); Ralha et al. (2013); and Villamor et al. (2014)
Manufacturing	Ajimotokan (2011); Andersson, Skoogh, and Johansson (2011); Andersson, Skoogh, and Johansson (2012); Barletta et al. (2014); van Beukering and Janssen 2001; Boulonne et al. (2010); Dong et al. (2012); Harun and Cheng (2011); Heilala et al. (2008); Jain and Kibira (2010); Johansson et al. (2009); Kibira, Jain, and McLean (2009); Lee, Kang, and Noh (2012); Lee, Kang, and Noh (2014); Lindskog et al. (2011); Mani et al. (2013); Paju et al. (2010); Shao, Bengtsson, and Johansson (2010); Shao et al. (2012); Solding and Petku (2005); Solding and Thollander (2006); Sproedt et al. (2015); Stasinopoulos et al. (2012); Tan, Ahmed, and Sundaram (2010); Thompson and Cavaleri (2010); Wang, Breme, and Moon (2014); Widok, Page, and Wohlgemuth (2011); Widok et al. (2012); Wohlgemuth, Page, and Kreutzer (2006); Xu et al. (2009); Zhou and Kuhl (2010); and Zhou and Kuhl (2011)
Mining	Maluleke and Pretorius (2013); Nageshwaraniyer et al. (2011)); O'Regan and Moles (2001); and O'Regan and Moles (2006)
Overview & review	Athanasiadis (2005); Axtell, Andrews, and Small (2002); Bras (2009); Dietterich et al. (2012); Fakhimi et al. (2013); Gomes (2009); Jayal et al. (2010); Kraines and Wallace (2006); Sterman (2014a), (2014b); Todorov and Marinova (2009); Todorov and Marinova (2011); and Zeng et al. (2011)
Social behaviour	Aguirre and Nyerges (2014); Faber and Jorna (2011); Israel and Wolf-Branigin (2011); Sircova et al. (2015); and Smajgl and Bohensky (2013)
Supply chain	Agusdinata et al. (2012); Awudu and Zhang (2012); Georgiadis and Besiou (2008); Georgiadis and Besiou (2010); Ghadimi and Heavey (2014); Golroudbary and Zahraee (2015); Jaegler and Burlat (2012); Jain, Lindskog, and Johansson (2012); Jain et al. (2013); Krejci and Beamon (2014); Liotta, Kaihara, and Stecca (2015); Rabe et al. (2012); Tian, Govindan, and Zhu (2014); and van der Vorst, Tromp, and Zee (2009)
Sustainable Development	Bockermann et al. (2005); Duran-Encalada and Paucar-Caceres (2012); Liu and Ye (2012); Moffatt and Hanley (2001); Nikolaou, Evangelinos, and Filho (2015); Okada (2011); Romero and Ruiz (2014); Su and Al-Hakim (2010); and Xu, Deng, and Yao (2014)
Tourism	Balbi, Giupponi, et al. (2013); Maggi, Stupino, and Fredella (2011); and Zhang, Ji, and Zhang (2015)
Transportation	DeLaurentis and Ayyalasomayajula (2009); Egilmez and Tatari (2012); Jin et al. (2012); Kitagawa, Sato, and Takadama (2014); Kuhl and Zhou (2009); Lee et al. (2012); Ma, Zhou, and Demetsky (2012); and Upreti et al. (2014)
Urban & community planning	Berger, Schreinemachers, and Woelcke (2006); Berman et al. (2004); van Duin and van der Heijden (2012); Gaube and Remesch (2013); Haase, Lautenbach, and Seppelt (2010); Jin et al. (2009); Katoshevski-Cavari, Arentze, and Timmermans (2011); Kuai et al. (2015); Muller and Aubert (2012); Piera, Buil, and Ginters (2015); Steinhoefel et al. (2012); Xu and Coors (2011); and Xu and Coors (2012)
Waste, recycling & reuse	Antmann et al. (2012); Blumberga et al. (2015); Georgiadis (2013); Matsumoto (2010); Shokohyar and Mansour (2013); Wang et al. (2014); and Yang, Sheng, and Shen (2011)
Water resources	Dai et al. (2013); Faezipour and Ferreira (2014); Giacomoni and Zechman (2010); Kanta and Zechman (2010); Khan, Yufeng, and Ahmad (2009); Mashhadi et al. (2014); Morales-Pinzon et al. (2015); Ozik et al. (2014); Sahin et al. (2014); Sahin, Stewart, and Porter (2015); Susnik et al. (2013); Winz, Brierley, and Trowsdale (2009); and Xu et al. (2002)

3.1.2. Addressing shortcomings in previously used models

Different fields in sustainability are more familiar with certain models when investigating sustainability related issues. While those well-established models have provided valuable insights, researchers discovered additional capabilities that simulation methods can supply. For example, well-adopted lifecycle analysis LCA (lifecycle analysis) methods are known for limitations such as fixed connections between technologies, constant or fixed functions of time, and inability to deal with certain specificities. Researchers have adopted simulation methods to complement such limitations of LCA (Ahn et al. 2009; Davis, Nikolić, and Dijkema 2009; Stasinopoulos et al. 2012). Also, many well-known models represent important components by homogenous 'average' entities (Balbi, Giupponi, et al. 2013; BenDor, Scheffran, and Hannon 2009). Simulation models, particularly ABMS enables explicit modelling of heterogeneous entities that are essential for some sustainability investigations (Balbi, Giupponi, et al. 2013; BenDor, Scheffran, and Hannon 2009; Gerst et al. 2013). In addition, simulation models have addressed existing models' limited ability in handling complex and interrelated connections commonly found in sustainability investigations. Some investigations require linking economic, social and environmental disciplines across time and space. Simulation methods have provided researchers with handy yet systematic way of handling such challenges (Aubert, Muller, and Ralihalizara 2015; Rebaudo and Dangles 2013).

3.1.3. Analysing uncertainties

The ability to explicitly incorporate and analyse uncertainties is a hallmark of simulation methods covered in this article. Researchers can take advantage of advanced probability and statistics and uncertainty data analysis with simulation models. Particularly, DEMS have numerous built-in standard tools to utilise probability distributions and statistical output analyses (Ahn et al. 2009; Law 2014). However, ABMS and SDMS have also been used to incorporate uncertainties in investigations (Awudu and Zhang 2012; Davis, Nikolić, and Dijkema 2009).

3.1.4. Addressing human experience

Numerous sustainability investigations involve assessing various human experiences. Although the consideration of human experience is critical for such studies, systematically incorporating human experience in research has been difficult or limited in scope. Researchers have adopted simulation modelling to add human experience components in their studies and reported valuable insights. Examples of human experience that researchers have been able to model using simulation models include people's decisions and their consequences in financial matters (Aubert, Muller, and Ralihalizara 2015; Balbi, Bhandari, et al. 2013; Martins et al. 2014; Smajgl and Bohensky 2013), satisfaction levels (Maggi, Stupino, and Fredella 2011; Upreti et al. 2014), other human dilemmas (Aguirre and Nyerges 2014; Balbi, Bhandari, et al. 2013; Gaube and Remesch 2013; Iwamura et al. 2014; Lyons and Duggan 2015; Rebaudo and Dangles 2013; Sircova et al. 2015; Zhang 2015), among others. Particularly, ABMS proved to possess an inherent structure to model individual's experience in the context of addressing sustainability issues.

3.1.5. Addressing conflicts and contradictions

Need to model conflicts and contradictions and to understand their consequences are common in sustainability investigations. Simulation models have been used effectively in addressing such conflicts or contradictions and have provided insightful suggestions and conclusions. Consequences of cooperation vs. competition for limited natural resources have been investigated (BenDor, Scheffran, and Hannon 2009), conflicts arising from planned actions versus autonomous decisions have been studied (Balbi, Bhandari, et al. 2013), and impacts on various policies on economic growth vs. environmental consequences have been modelled (Gerst et al. 2013). Researchers proved that simulation models can be used to understand such conflicts and suggest appropriate conflict resolutions. Also, simulation models have been used to detect any contradictions or inconsistencies that are difficult to find only with metal models (Agusdinata et al. 2012; Martins et al. 2014).

3.1.6. Dealing with different and longer timeframe

Some sustainability studies require longer timeframe, sometime even beyond a human lifetime or several generations. Numerous researchers took advantage of simulation methods where timeframe can easily be extended as they wish. Temporal scales used in the reviewed studies range from just a few days to over 1000 years (Balbi, Bhandari, et al. 2013; Berman et al. 2004; Iwamura et al. 2014; Li, Dong, and Li 2012; Martins et al. 2014; Rogers et al. 2012; Saysel, Barlas, and Yenigün 2002). Such an ability in simulation methods is essential for certain inquiries that require expanded timeframe.

3.2. Shortcomings of simulation modelling for sustainability investigations

Despite many merits of using simulation models for advancing sustainability science, it will be useful to point out some shortcomings, especially to sustainability researchers who contemplate adopting simulation modelling for their investigations and to simulation researchers who can further advance simulation technology to become more suitable for sustainability scholarship.

3.2.1. Issues of validation

Any simulation models need to be verified and validated before they can be used for various investigations. Verification is a process to ensure 'building a model right' while validation is a process to ensure 'building a right model' (Law 2014). Verification checks internal consistencies in a model, but validation checks external consistencies in a model. In sustainability science, data necessary for validating simulation models are not always readily available. Also, certain simulation models depending on how they are constructed are not easily to be validated. This process of validation is not an exact science, rather requires significant efforts and creativity to ensure that people who adopt simulation models are sufficiently convinced in the validity of the models. Researchers in sustainability simulation need to be actively engaged in sharing and disseminating best practices of validation methods and continue to develop new ways to achieve it.

3.2.2. Assumptions

Any simulation model starts with a certain set of assumptions. Research goals should clearly indicate any assumptions and results should be interpreted in the context of those assumptions. Sustainability researchers who use simulation modelling need to be aware of the importance of highlighting any assumptions made in their simulation models in order to ensure the integrity of their studies. Without explicitly stated assumptions in research papers, readers may be misled by research results. Articulating rationales behind the assumptions can also help advancing sustainability science.

3.2.3. Education

Simulation methods are not necessarily well-known tools to researchers in sustainability fields. At the same time, expert knowledge is critical in simulation modelling. Experts in simulation technology may not be able to capture important aspects in certain sustainability fields thus miss entirely critical goals, components, relationships in their modelling and result analysis. Although domain experts may not need to acquire simulation knowledge to experts' level, it is critical that they are well versed with how simulation methods can help and their limitations. New textbooks have been written recently and numerous tutorials have been published (Kelton, Sadowski, and Zupick 2014; Macal and North 2013; Wilensky and Rand 2015). However, further continuous efforts to address this issue are necessary.

3.2.4. Software

As many simulation models are complex, simulation software is likely to be adopted and used in sustainability investigations. Numerous investigations have been carried out by a team of researchers where some members have professional programming skills. Still, accessible simulation software is critical since they enable quick prototype simulation model building and domain experts themselves can construct and run simulation models. Although there have been significant progresses in available simulation software and their usability, researchers need to be aware of their limitations. Sometimes simulation modelling has been limited by the capability of software adopted. Refining currently available software as well as creating new software for sustainability scientists are necessary and desirable.

4. Application areas

The papers reviewed in this article cover a wide range of topics in simulation modeling for sustainability. As a consequence, it is difficult to provide a detailed review of all the papers. Therefore, an aggregate summary of papers under each application area is provided in this section.

4.1. Agriculture, Aquaculture & Livestock

Decisions made by or for farmers (Balbi, Bhandari, et al. 2013; Belcher, Boehm, and Fulton 2004; Li, Dong, and Li 2012; Rebaudo and Dangles 2013; Saysel, Barlas, and Yenigün 2002; Schreinemachers and Berger 2011), fishermen (BenDor, Scheffran, and Hannon 2009; Martins et al. 2014), hunters (Iwamura et al. 2014), affect future environmental, economic and social sustainability not only in their respective communities, but also in extended regions. However, such decisions do not necessarily result in uniformly positive or negative consequences for sustainability. Informed decisions based on insights gained from complex interactions among involved eco-system's components need to be made in order to achieve desirable sustainable objectives. Many decision variables and independent factors were considered in the simulation studies reported in the papers, including crop rotations, irrigation management, demographic growth, dynamics of animal food chain, food-web in sea, animal population, and income levels. How proposed policies might have impact on sustainable indicators was explored under various scenarios. It is notable that none of the papers in this category adopted DEMS.

4.2. Construction

Projects reported in the papers under this category include earthmoving operations, road construction, building, paving and infrastructure projects. Earlier models used in construction field were limited that they tend to be static and deterministic (González and Echaveguren 2012). Simulation models were proposed as they provide additional capabilities to overcome numerous limitations of static and deterministic models. It is notable that emissions during a construction project were a predominant factor that has been investigated in this category's papers (Ahn et al. 2009, 2010; González and Echaveguren 2012; Li and Lei 2010; Mallick et al. 2014; Zhang 2015). It is also noted that more than half of the papers classified to this category adopted DEMS as their primary simulation paradigm, perhaps because emissions could directly be calculated from the DEMS results.

4.3. Ecosystem & climate

The group of papers in this category takes up a macro view on ecosystem and climate issues and tries to gain insights from simulation model results. Compared to other categories, the geographic scope covered by this category's papers was wider, involving at least local communities (Aubert, Muller, and Ralihalizara 2015; Learmonth et al. 2011; Schreinemachers, Berger, and Aune 2007) but often all the way to international levels (Gerst et al. 2013; Mizuta and Yamagata 2001). Also the temporal scale of their simulation studies was longer, even extending to thousand years (Rogers et al. 2012). Forest management and its interaction with surrounding communities have been also explored (Aubert, Muller, and Ralihalizara 2015; Machado et al. 2015; Munthali and Murayama 2014). Impact of climate policy at national level and international level has been investigated (Gerst et al. 2013). Trading greenhouse gas emissions between countries has been studied (Mizuta and Yamagata 2001). Other investigations involving human-environmental interactions have also been conducted. It is notable that in this category all but one used ABMS.

4.4. Energy

Energy is the critical element in achieving the goal of sustainable development. While many other papers surveyed in this paper addressed energy issues one way or another, the papers classified under this category explicitly dealt with energy policies, optimisation and effective use of energy sources, or analysis methods focused on energy. The group of papers in this category addressed energy diversification, renewable energy policies, behaviour of energy market along with energy incentives and policies, energy management systems, optimal energy mixture, smart grid and other issues. Types of energy sources covered in these papers were also numerous covering biofuel, wind, solar, fossil and hybrid systems. Also, understanding of energy policies' impact on various issues at national level has been investigated using simulation models (Aslani, Helo, and Naaranoja 2014; Barisa et al. 2015; Franco, Castaneda, and Dyner 2015; Jager, Schmidt, and Karl 2009; Qudrat-Ullah 2013; Robalino-López, Mena-Nieto, and García-Ramos 2014). On the other hand, effects of employing decentralized energy systems have been investigated at regional and company levels (Hollmann 2006; Reddi et al. 2013). Limitations of Life Cycle Assessment (LCA) were discussed, and simulation models were suggested to complement traditional methods such as LCA (Davis, Nikolić, and Dijkema 2009; Miller et al. 2012). It is notable that none of the papers in this category used DEMS.

4.5. Human health

How to improve or maintain human health is important in addressing the social aspect of the triple bottom line model. Some issues considered in the papers under this category were directly connected to human health such as soil and water contamination (McKnight and Finkel 2013). Some involved health care systems such as clinics and hospitals (Alexopoulos et al. 2001; Petering et al. 2015; Viana 2014), mobile health care system (Djanatliev and German 2013), rural health care system (Kumar and Kumar 2014). Others investigated policy related issues at national level (Lin et al. 2013; Lyons and Duggan 2015). Papers for health care systems addressed efficiency issues by developing simulation models to optimise them. Also, the responsibility of the health care sector in the environment such as through generated emissions was considered and investigated using simulation studies (Fakhimi et al. 2014).

4.6. Information systems

Information and communication technologies (ICT) have numerous impacts on sustainability including those from the lifecycle of ICT hardware themselves, from the services provided by ICT applications and other emerging effects on the society through product-to-service shift in consumption or rebound effects in transportation (Erdmann and Hilty 2010; Hilty et al. 2006). Such impacts were defined and typically classified into three orders of effects (first, second and third) in the papers under this category. Since such multiple order effects can be either positive or negative, benefits gained from one area can easily be offset by negative impacts occurred in other area. In order to understand such dynamics under various scenarios, simulation models were developed and used as a decision support tool. Lovrić, Li, and Vervest (2013) developed an ABMS to effectively manage revenue streams in public transportation system, by utilising advanced analytics on data collected through smart cards.

4.7. Land use

The group of papers in this category has investigated issues relating to land use including farms, forest, wetland and coast. Changes in land uses and purposes are interrelated with other environmental and social issues. Such mutual impacts and sometimes direct conflicts are complex, so simulation studies have been conducted to develop deeper understanding. Some of the factors incorporated into the simulation models were demographic changes in farming communities, changes in crops, different levels of incentives, tax policies, among others. Deforestation and desertification due to land use changes have also been investigated. In this category, all the papers have adopted ABMS with one exception using SDMS (Chen, Chang, and Chen 2014).

4.8. Manufacturing

Sustainable manufacturing, as defined by the US Department of Commerce, is 'the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound'. (Department of Commerce 2015) To realise the vision of sustainable manufacturing, products by themselves need to be sustainable, processes employed to make the products need to be sustainable, and manufacturing systems that coordinate the processes need to be sustainable. Issues in achieving these goals altogether have been addressed by simulation modelling. Limitations of lifecycle assessment (LCA) in manufacturing applications led to the development of supplementary or combined simulation models (Andersson, Skoogh, and Johansson 2012; van Beukering and Janssen 2001; Harun and Cheng 2011; Johansson et al. 2009; Lee, Kang, and Noh 2012; Lindskog et al. 2011; Mani et al. 2013; Paju et al. 2010; Sproedt et al. 2015; Stasinopoulos et al. 2012). Plans and scenarios for reducing energy consumption, greenhouse gas emissions and material uses were investigated using simulation models (van Beukering and Janssen 2001; Lindskog et al. 2011; Solding and Thollander 2006; Sproedt et al. 2015). Meeting social needs during manufacturing activities have also been simulated along with other dimensions (Ajimotokan 2011; Lee, Kang, and Noh 2012). Beyond individual manufacturing systems, impact of government's regulations on sustainable manufacturing has been simulated (Dong et al. 2012) and comparison between conventional bookstore selling and e-commerce has been studied using simulation models (Xu et al. 2009). Among all the application areas, this category contains the most number of papers.

4.9. Mining

Mining is critical to the environment since it extracts and processes mineral resources that are not renewable. During the lifecycle of mining, various environmental consequences occur such as greenhouse gas emissions, description of lands, disturbances of water resurrect, noise and dust pollutions among others. At the same time, mining is an essential component in economic development. Four papers in this category look into different issues of mining. Impacts from different environmental, economic, corporate and governmental policies on mining and the interactions between those policies were modelled and studied (Maluleke and Pretorius 2013; O'Regan and Moles 2001, 2006). SDMS was adopted for those studies in the South America and Ireland, but also for scenarios of international investment. Nageshwaraniyer et al. (2011) used DEMS to optimise operation decisions during mining activities, utilising real-time information collected from field sensors and connected to a large information system such as Enterprise Resource Planning system (Moon 2007).

4.10. Overview & review

Papers assigned to this category do not present results from simulation-based studies, rather provide overviews or reviews of certain aspects of simulation modelling for sustainability. Current status, trends or challenges of certain technologies were explained and discussed (Axtell, Andrews, and Small 2002; Bras 2009; Dietterich et al. 2012; Gomes 2009; Kraines and Wallace 2006; Sterman 2014a, 2014b). Literature reviews on different subjects were also conducted (Athanasiadis 2005; Zeng et al. 2011). To the best knowledge of the author, only other review paper published on a similar subject prior to this article was by Fakhimi et al. (2013). They reviewed the literature on simulation of sustainable development. They covered the period between 1970 and 2012; however, only papers under the subject category of 'Operations Research Management Science'. A total of 164 papers were analysed by (i) simulation techniques, (ii) aspects of the triple bottom line model and (iii) application areas.

4.11. Social behaviour

As Faber and Jorna (2011) pointed out, 'although sustainability is mostly synonymous with ecology or environmental issues, … it is not nature itself that, acting on its own, produces destruction; it is our individual and collective human behavior …' The five papers classified under this category explicitly focused on understanding human social behaviour in the context of sustainable development. Appropriateness of ABMS in studying social sustainability was discussed by Faber and Jorna (2011), and Israel and Wolf-Branigin (2011). How public participation works in collective sustainable management was studied in ABMS model (Aguirre and Nyerges 2014). As illustrated in 'Tragedy of the Commons' (Hardin 1968), the social dilemma was modelled utilising ABMS where individual differences were maintained, then emerging patterns were observed and discussed (Sircova et al. 2015). A particular social issue of poverty was examined under various fuel subsidy plans and cash payment plans (Smajgl and Bohensky 2013). It is notable that all five papers under this category adopted ABMS as their simulation method.

4.12. Supply chain

The group of papers in this category addressed issues arising from supply chains, covering biofuel supply chains, food supply chains, electrical and electronic equipment supply chains, and production supply chains. The role of efficient supply chain management was emphasised in order to reap the ultimate benefits from technological advances made such as in biofuels (Agusdinata et al. 2012; Awudu and Zhang 2012). The concept of closed-loop supply chains has been discussed and investigated while incorporating recycling, remanufacturing and reuse activities into the supply chains (Georgiadis and Besiou 2008, 2010; Golroudbary and Zahraee 2015). Food supply chains have been simulated to meet the demands on food quality and associated sustainability issues (Krejci and Beamon 2014; van der Vorst, Tromp, and van der Zee 2009). How to choose or design a desirable green supply chain has been studied with emission control in mind (Jaegler and Burlat 2012; Jain, Lindskog, and Johansson 2012; Jain et al. 2013; Rabe et al. 2012; Tian, Govindan, and Zhu 2014). Simulation models were considered particularly appropriate in handling flexibility in their analyses (Rabe et al. 2012; van der Vorst, Tromp, and van der Zee 2009). Adoption of hybrid simulation models to accommodate different purposes and levels of detail for a same investigation has also been suggested (Jain, Lindskog, and Johansson 2012; Jain et al. 2013).

4.13. Sustainable development

This group of papers addressed sustainable development at national (Bockermann et al. 2005; Moffatt and Hanley 2001) groups of firms (Liu and Ye 2012; Romero and Ruiz 2014; Xu, Deng, and Yao 2014) or individual corporate (Duran-Encalada and Paucar-Caceres 2012; Nikolaou, Evangelinos, and Filho 2015; Okada 2011; Su and Al-Hakim 2010) levels. As industrial development and activities were planned and increased, the complex and interrelated issues with all three dimensions of sustainable development (i.e. economic, environmental and social) have been investigated. Simulation models were proposed, constructed and used to develop insights into necessary combinations of components towards achieving goals of sustainable development, especially by overcoming limitations of common models and tools that had been adopted for understanding sustainable development. Corporate behaviours and policies have been studied, which were influenced or influencing the environment, economic and other factors such as employment levels (Bockermann et al. 2005; Duran-Encalada and Paucar-Caceres 2012; Liu and Ye 2012; Nikolaou, Evangelinos, and Filho 2015; Okada 2011; Su and Al-Hakim 2010). How a simulation model can be constructed using a Global Reporting Initiative report was illustrated by Duran-Encalada and Paucar-Caceres (2012).

4.14. Tourism

All three papers in this category addressed all three dimensions of the triple bottom line model since their issues involve potential effects on the environment and resources due to increasing tourists and associated activities in tourist areas, implications on economy by the levels of tourism, and closely tied social aspects such as satisfactory quality of life and experience by the residents and the tourists. Effective decisions concerning the tourism could be made when important interactions among involved entities were considered and various trade-off consequences were evaluated under different scenarios. Two papers (Balbi, Giupponi, et al. 2013; Maggi, Stupino, and Fredella 2011) used ABMS to evaluate future scenarios for policy and decision-making support for tourism in an Alpine region in Italy and in the Mediterranean area. The third paper (Zhang, Ji, and Zhang 2015) adopted SDMS along with other techniques such as neural networks to investigate impacts of different scenarios in Tibet Autonomous Region in China.

4.15. Transportation

Transportation is an essential element in today's society and for sustainable development. This group of papers addressed a variety of sustainability-related topics arising from different transportation modes such as air transportation, highway transportation, road transportation and public transportation by buses or bicycles. Impact of different policies on highway system in terms of greenhouse gas emissions has been investigated (Egilmez and Tatari 2012). Also, traffic rules at road intersections have been simulated in order to optimise scheduling of vehicles' departure times (Jin et al. 2012). Route optimisation for emergency transportation (Kitagawa, Sato, and Takadama 2014) as well as university transportation (Upreti et al. 2014) have been studied. Use of bicycles for sustainability and its impact on sustainability have been simulated and analysed (Lee et al. 2012). Advances in transportation technology such as cooperative adaptive cruise control system have been analysed in simulation models in order to assess their potential contributions to sustainability (Ma, Zhou, and Demetsky 2012).

4.16. Urban & community planning

More than half of the world's population now live in cities and the proportion continues to grow (United Nations Department Economic and Social Affairs (DESA) 2014). This category contains papers addressing issues involved in urban planning along with

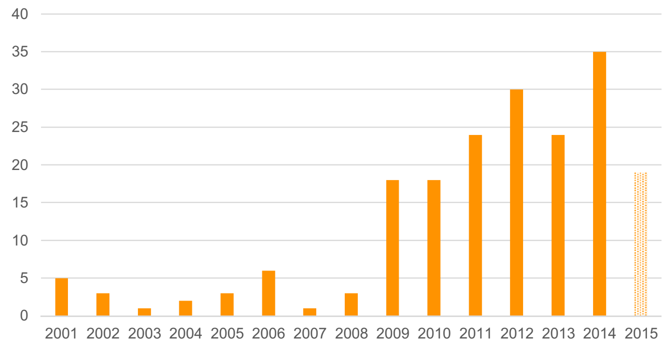

Figure 1. Number of publication by year.

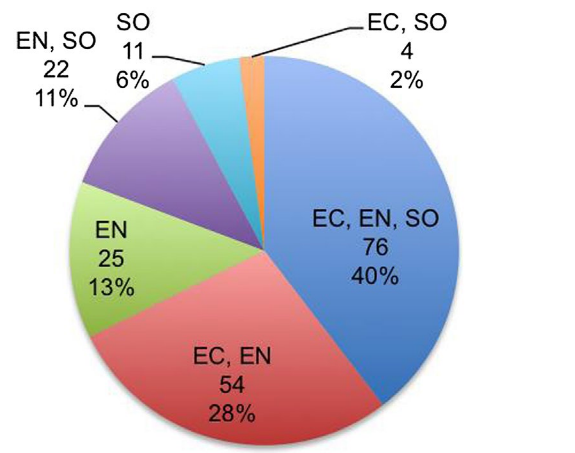

Figure 3. Coverage of three dimensions (EC – economical, EN – environmental, SO – social).

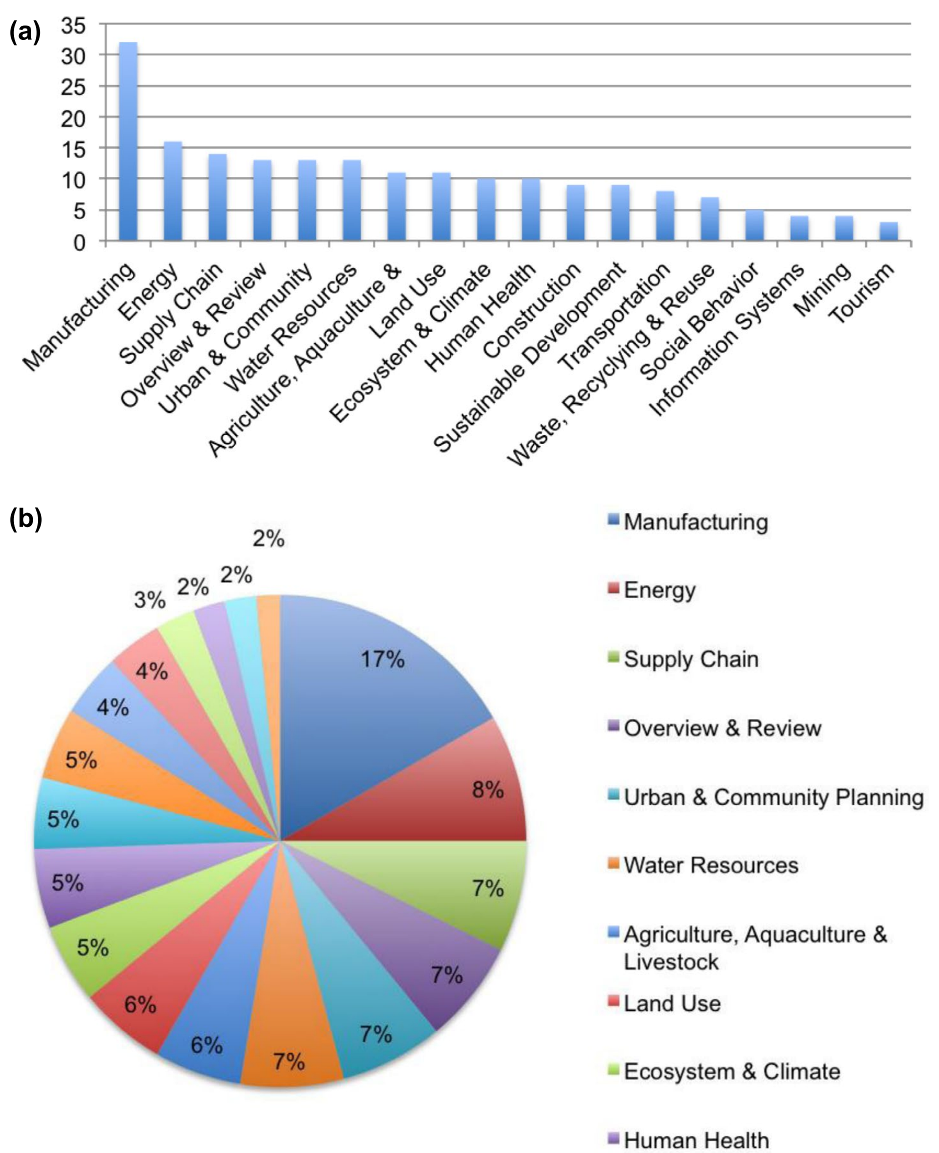

Figure 2. Number of papers for each category (a) bar chart (b) pie chart.

a few papers on planning of unique communities. Cities that were growing as well as shrinking have been modelled in order to understand their future trajectories and corresponding influence on sustainability issues (Gaube and Remesch 2013; Haase, Lautenbach, and Seppelt 2010). Specific issues such as noise control and optimisation of traffic-related sustainability issues have been studied (van Duin and van der Heijden 2012; Katoshevski-Cavari, Arentze, and Timmermans 2011). Understanding urban residential development, sometimes with a focus on social segregation, has also been investigated (Steinhoefel et al. 2012; Xu and Coors 2011, 2012). Simulation studies have been conducted in communities different than urban settings, including less-favored rural areas in developing countries (Berger, Schreinemachers, and Woelcke 2006), an Arctic community (Berman et al. 2004) and a local community in Madagascar (Muller and Aubert 2012). The impacts of development policy scenarios on such communities as well as interactions with locally unique factors have been investigated.

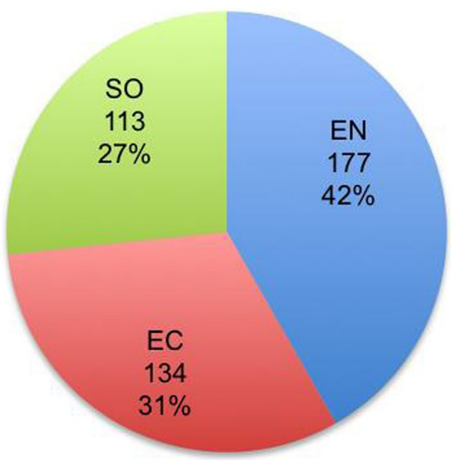

Figure 4. Coverage of three dimensions.

4.17. Waste, recycling & reuse

Effectively managing wastes, recycling, remanufacturing and reuse activities can contribute to sustainability positively. However, these activities do not occur in vacuum, requiring necessary energy, resources, generation of by-products such as emissions and waste, investment, infrastructure, public acceptance, government involvement, subsidy policies, among many others. Unless a holistic system view is instilled, potential benefits directly from these activities can easily be offset or overcome by other costs. Various simulations models have been developed to deal with issues ranging from solid waste (Antmann et al. 2012), to battery waste (Blumberga et al. 2015), to electrical and electronic equipment waste (Matsumoto 2010; Shokohyar and Mansour 2013), to auto parts (Matsumoto 2010; Wang et al. 2014), and to paper (Georgiadis 2013). Simulation optimisation was used to suggest best practices (Antmann et al. 2012; Shokohyar and Mansour 2013).

4.18. Water resources

Water, one of the most important resources for sustaining human being, is unfortunately a limited asset. With the increasing

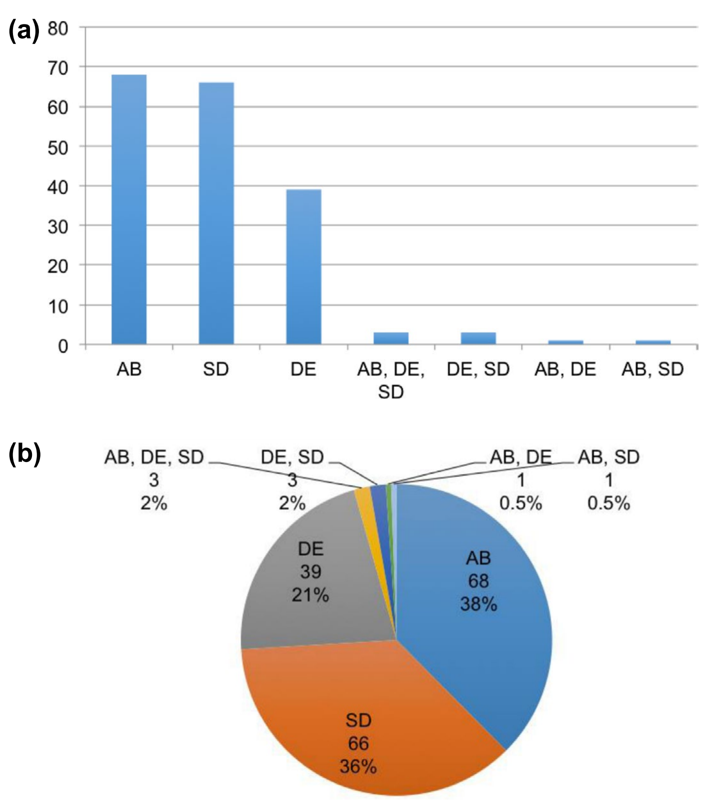

Figure 5. Adoption of three simulation methods (a) bar chart (b) pie chart (AB – agent-based modelling and simulation; DE – discrete event modelling and simulation; SD – system dynamics modelling and simulation).

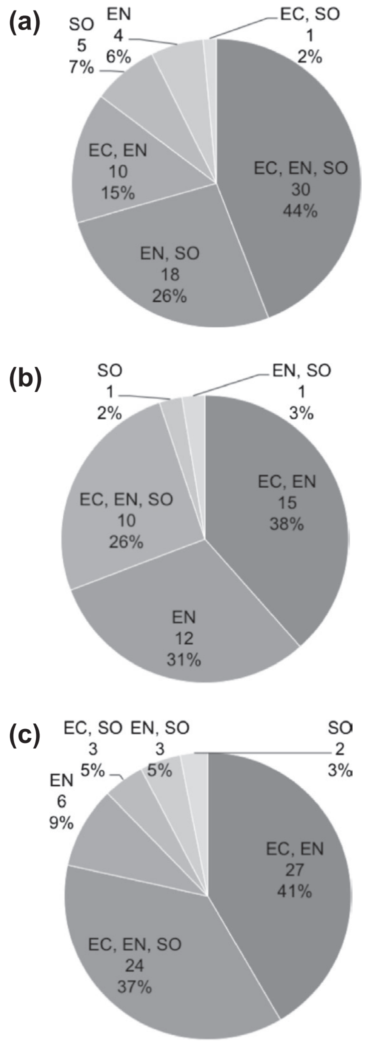

Figure 6. Coverage of three dimensions by each group of papers according to simulation types (a) For papers adopting ABMS (b) For papers adopting DEMS (c) For papers adopting SDMS.

population associated with increasing demand on water for industrial and agricultural uses among others, understanding important issues of water resources became critical. Numerous scenarios have been developed and investigated to gain insights into which one might have what kind of impacts on water resource management (Dai et al. 2013; Faezipour and Ferreira 2014; Giacomoni and Zechman 2010; Mashhadi et al. 2014; Sahin et al. 2014; Sahin, Stewart, and Porter 2015; Susnik et al. 2013; Xu et al. 2002). Interactions among key entities such as customers, policy-makers, water cycle components, food and security have been studied (Kanta and Zechman 2010; Khan, Yufeng, and Ahmad 2009; Susnik et al. 2013).

5. Data analysis

The number of publications on simulation modelling for sustainability is certainly on the rise as shown in Figure 1. Considering that the article includes only a portion of papers published until 31 May 2015, a significantly more number of papers have been published since 2009 and the increasing trend seems to hold. Possible reasons for the upward trend are increasing number of researchers across many disciplines who became interested in sustainability, better awareness of the capability of simulation modelling among domain experts, and better availability of simulation tools and computing power.

The number of papers that were classified into one of the 18 categories is shown in Figure 2. A wide range of questions have been addressed by simulation models as evident from the scope of application areas. But it is notable that the category of 'Manufacturing' has the most number of papers, more than double of the next category of 'Energy'. The manufacturing research community has a long history of utilising simulation modelling, particularly DEMS. When the notion of sustainable manufacturing became critical in recent years, their expansion to address sustainability issues may have been natural so a possible explanation for the high number.

Figure 3 shows distributions by dimensions of sustainable development that were addressed by the papers. Almost 40% of the papers covered all three dimensions of the triple bottom line model of sustainable development ('environmental', 'economic' and 'social' domains), followed by those papers addressing only both 'economic' and 'environmental' (28%) domains. The papers dealing with both 'economic' and 'social' dimensions are the least (2%). Also only 6% of the papers addressed 'social' domain exclusively. Figure 4 presents a result after papers addressing multiple dimensions are added to individual domain so that only three domains' statistics can be shown. 'Environmental' dimension (42%) is the most covered one, followed by 'economic' (31%) then 'social' (27%).

The most adopted simulation method was ABMS, but SDMS was used almost equally as ABMS. DEMS was adopted the least among the three (Figure 5). Although combinations of the simulation methods and hybrid simulation models appeared, their numbers are relatively insignificant compared to those adopting a single method. In order to develop further insights, papers using a particular simulation method were analysed separately as presented in Figure 6. A notable observation from these three charts is that when social dimension is involved in study questions, ABMS is the method used most frequently while DEMS is used the least frequently.

There are various commercial as well as free software packages available to assist simulation modelling processes (INFORMS 2014). Such software is critical in carrying out simulation projects especially when the scope and complexity are great and when researchers' resources do not contain computer coding expertise. While many papers surveyed in this article used one or more software, not all of them reported which software packages they used. For those papers that explicitly mentioned software packages used, a statistics was gathered as shown in Figure 7. Only those software packages used three times or more in the surveyed papers were included in Figure 7. 'Vensim' was adopted the most frequently and 'Arena' was the next, followed by 'NetLogo', 'Powersim' and 'Stella'. Software packages used for each simulation method are shown in Figures 8–10. It is notable that 'Arena' has been the predominant software adopted for DEMS.

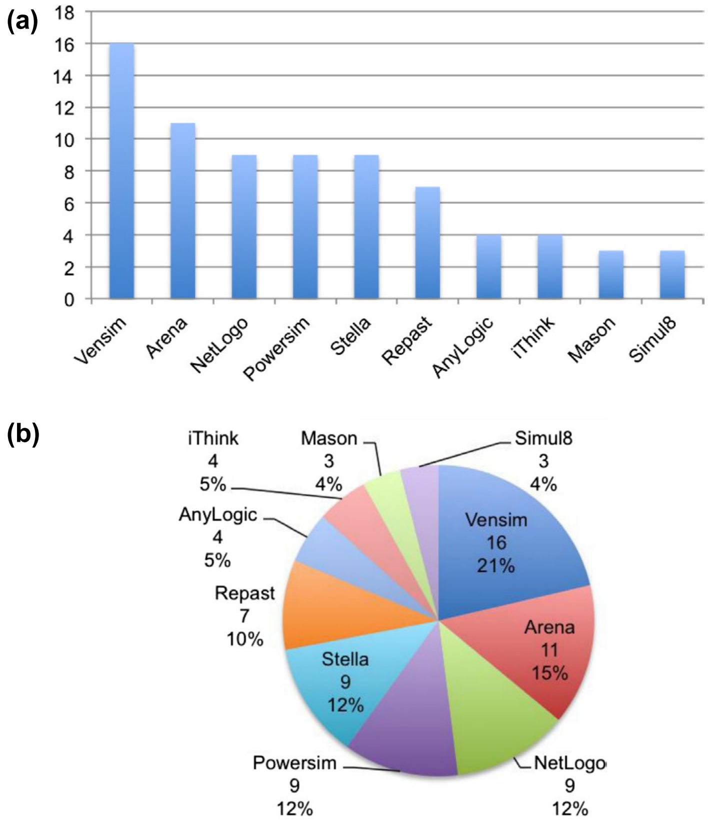

Figure 7. Uses of software packages (a) bar chart (b) pie chart.

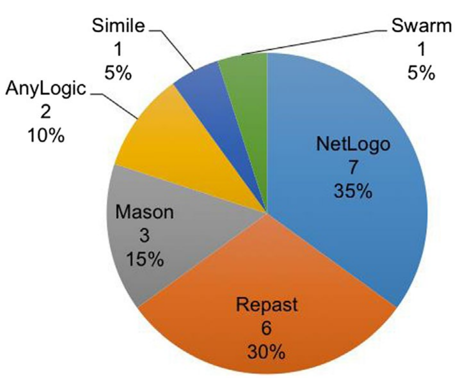

Figure 8. Uses of software packages for papers adopting ABMS.

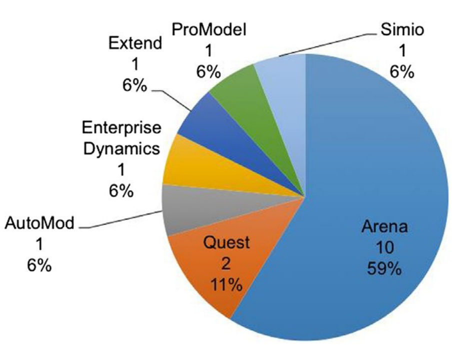

Figure 9. Uses of software packages for papers adopting DEMS.

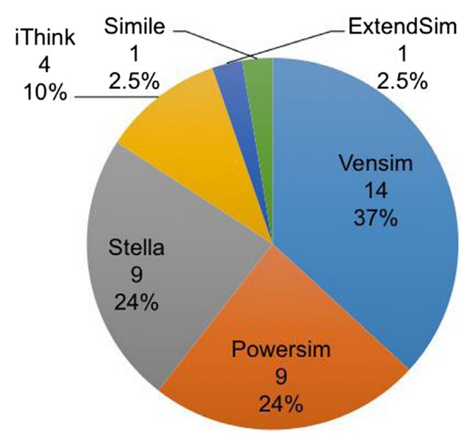

Figure 10. Uses of software packages for papers adopting SDMS.

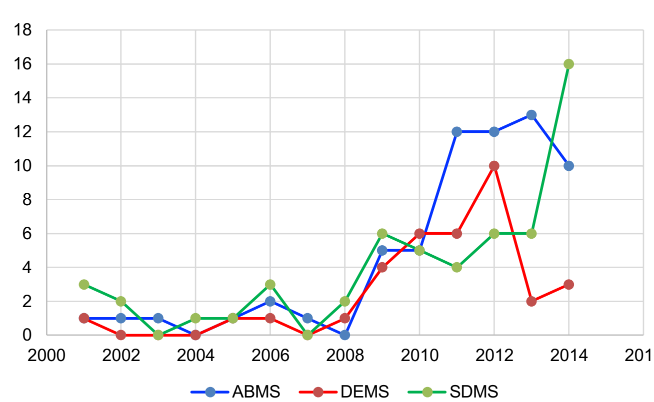

Figure 11. Uses of individual simulation method by year.

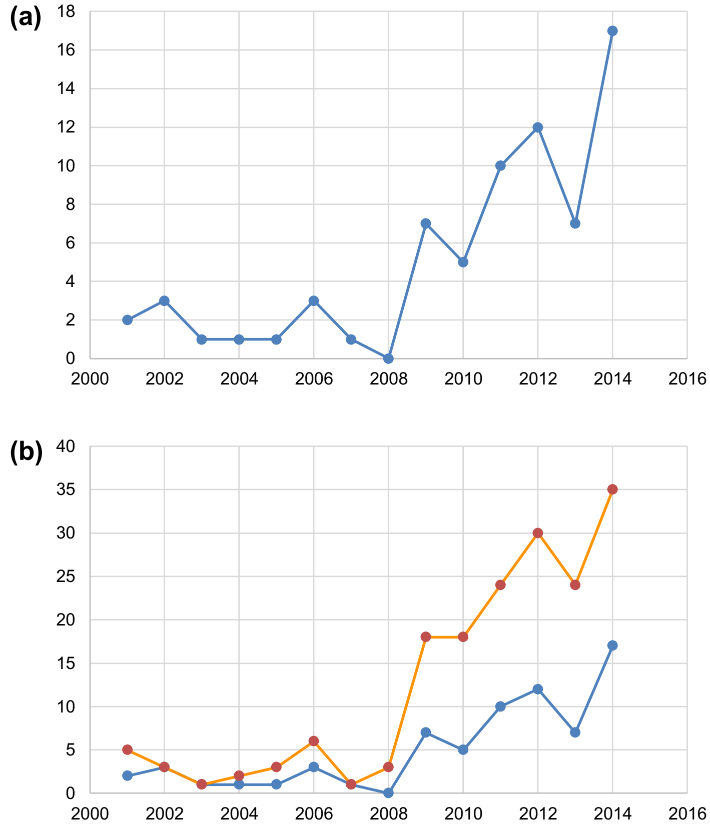

Figure 12. Number of papers addressing all three dimensions by year (a) only the papers addressing all three dimensions together (b) papers addressing all three dimensions (blue) vs. all papers (orange).

6. Discussion and conclusion

As simulation techniques advance and interests on sustainability grow, it is remarkable to observe that so many application areas have already been covered and so diverse research questions have already been addressed in the collection of the papers surveyed in this article. Many of the study questions in sustainability can only effectively be addressed by simulation modelling, therefore, it is not surprising that simulation modelling made good contribution towards addressing sustainability issues. But it is also anticipated that simulation modelling will continue to deepen and widen its contributions to sustainability in future.

In the collection of papers reviewed here, simulation studies have been conducted in already 43 different countries. Since sustainability truly concerns every nation and every person on earth, researchers in other countries will be utilising simulation techniques for their unique issues and new international investigations. As researchers in other fields become aware of how simulation models have been developed and used to address related problems in some fields, they can certainly be motivated to find additional research revenues. As computing powers and software technologies continue to evolve, more useful simulation technologies will accompany them and consequently stimulating more research projects that could not be done before.

ABMS, DEMS and SDMS are three main simulation methods used today. However, it has been observed that numerous papers surveyed in this article also adopted other tools to complement the simulation methods. For example, optimisation has been combined with simulation (Jin et al. 2012; Kitagawa, Sato, and Takadama 2014; Krejci and Beamon 2014; Schreinemachers and Berger 2011; Shokohyar and Mansour 2013), and machine learning techniques have also been used in conjunction with simulation (Sircova et al. 2015; Smajgl and Bohensky 2013; Tian, Govindan, and Zhu 2014; Zhang, Ji, and Zhang 2015). It is expected that researchers find simulation modelling as useful techniques to complement other tools, or vice versa.

A trend observed in the adoption of the three simulation methods (Figure 11) indicates that the research community has used ABMS more in recent years than the other two methods. This phenomenon might have resulted from increased awareness of and education on this method, wider availability of software, propagation effects, reinforced by increased publications in recent years, among others.

Another trend in the simulation community that also starts appearing in the collection of reviewed papers in this article is the adoption of hybrid simulation models. In those studies, two or more simulation methods (e.g. ABMS, DEMS and SDMS) are combined in a single simulation model, allowing multiple viewpoints to be represented at the same time. While there is still debate on how one can clearly distinguish different simulation methods, hybrid simulation modelling can certainly help modelling different approaches conceptually in a single model. However, the number of reported studies exploring hybrid simulation models for sustainability is relatively insignificant (Figure 5), indicating potential research venues.

Figure 12 shows the number of papers addressing all three dimensions – economic, environmental and social. Although there is an increasing trend in this number, when compared with the total number of papers reviewed (Figure 12(b)), the increasing rate seems to be correlated with the rate of overall number. As pointed out in the previous section, 'social' dimension is the least investigated aspect among the three dimensions of the triple bottom line model of sustainable development. This gap may be another venue to explore in future.

While the majority of the surveyed studies used simulation models for typical uses as described in Section 1, there are some papers exploring new techniques and tools to enhance the capacity of simulation (Andersson, Skoogh, and Johansson 2012; Boulonne et al. 2010; Davis, Nikolić, and Dijkema 2009; Shao, Bengtsson, and Johansson 2010; van der Vorst, Tromp, and van der Zee 2009). Likewise, some research results are expected to contribute to advancing simulation techniques themselves, still motivated by addressing sustainability issues.

It would be useful to point out limitations of this article so that future work may address them. First, two primary search engines (Scopus and Google Scholar) were used to search papers. While extensive searches were conducted by reaching 2000 articles from each of the search engines, it is always possible that some papers might have been missed due to several reasons including search terms used and indexing mechanisms built in the search engines. Second, certain fields may use different terms to refer to simulation and sustainability. If this is a case, it is also possible that some papers were not included in this article. Third, there are other simulation methods beyond the three used in this article (ABMS, DEMS and SDMS) such as Monte Carlo Simulation and mathematical modelling-based simulation. Others were decided not to be included in this article so that clear analytic understanding is possible from the three well-established methods. But this doesn't mean that the results or insights gained from those studies are not significant. Fourth, while the classification schemes were established after numerous readings of the surveyed papers, some papers certainly address more than one category particularly in application areas. However, each paper was assigned to one category based on a judgement call on which category was weighed more in the paper. It might be useful to develop an alternative classification scheme where multiple assignments can be done without losing clarity. Fifth, some of the papers do not report any commercial software they used. Therefore, the analysis on the software is based on the released information only. Finally, new papers are being published each day. Periodically this review paper will need to be updated to reflect the growing body of knowledge on the subject.

Perhaps the most well-publicised simulation study in the field of sustainability was the work commissioned by the Club of Rome, which was published in 'The Limits to Growth' (Meadows et al. 1972). They used SDMS as their base simulation method and conducted the study to explore what can happen when the growth in population and economic activities would continue but resources would remain limited. Although the study raised significant awareness of critical issues surrounding sustainability and deserves credit for highlighting the usage of simulation modelling, it was sometimes unfairly criticised by uninformed perceptions on what simulation results should be. Put succinctly, Box (1976) said, 'all models are wrong but some are useful'. It is necessary and critical for researchers using simulation models to continue their practice of presenting their objectives clearly, stating their assumptions explicitly, underlying limitations of their studies, and articulating valuable insights gained.

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