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Simulation Modeling 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 Modeling 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 modeling 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 analyzed for application areas, simulation methods, and dimensions of the triple bottom line model of 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 modeling than any other available methods. Simulation is a kind of modeling, but refers to a group of methods that imitate the behaviors 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 behaviors 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 Modeling and Simulation (Gilbert 2008), Discrete-Event Modeling and Simulation (Law 2014), and System Dynamics Modeling and Simulation (Sterman 2000).

Agent-Based Modeling and Simulation (ABMS) is a simulation method in which agents are modeled to interact with each other and their environment. Emerging behaviors, 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.

Discrete-Event Modeling and Simulation (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 modeled explicitly and their collective consequences in the system are analyzed statistically.

System Dynamics Modeling and Simulation (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 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, conceptualizing a complex system at a more aggregate level.

This article presents a review of the literature on simulation modeling for sustainability, published

between 2000 and 2015 (May 31). 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 modeling 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.

This article is divided into five sections. How papers were selected for review and organized is explained in Section 2. Section 3 provides synopses of papers in each application area. Analyses of data tagged from the reviewed papers are presented in Section 4. The article concludes in Section 5 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 as between January 1, 2000 and May 31, 2015. 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. 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 between January 1, 2000 and May 31, 2015 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:

       i) Agent-Based Modeling and Simulation (ABMS)
       ii) Discrete-Event Modeling and Simulation (DEMS)
       iii) System Dynamics Modeling and Simulation (SDMS).

Finally, a total of 192 papers were identified for the review in this article. Out of the 192 papers, eleven (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 Behavior, (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.

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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 (United Nations General Assembly 1987) - environmental, economic, and social, and the other is according to methods of simulation - ABMS, DEMS, and SDMS. More detail analyses on these classification schemes are presented in Section 4.

3. 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 detail review of all the papers. Therefore, an aggregate summary of papers under each application area is provided in this section.

Agriculture, Aquaculture & Livestock

Decisions made by or for farmers (Balbi 2013, Belcher 2004, Li 2012, Rebaudo 2013, Saysel 2002, Schreinemachers 2011), fishermen (BenDor 2009, Martins 2014), hunters (Imamura 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.

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 (Gonzalez 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 2009, Ahn 2010, Gonzalez 2012, Li 2010, Mallick 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.

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 2015, Learmonth 2011, Schreinemachers 2007) but often all the way to international levels (Gerst 2013, Mizuta 2001). Also the temporal scale of their simulation studies was longer, even

extending to thousand years (Rogers 2012). Forest management and its interaction with surrounding communities have been also explored (Aubert 2015, Machado 2015, Munthali 2014). Impact of climate policy at national level and international level has been investigated (Gerst 2013). Trading greenhouse gas emissions between countries has been studied (Mizuta 2001). Other investigations involving human-environmental interactions have also been conducted. It is notable that in this category all but one used ABMS.

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 were explicitly deal with energy policies, optimization 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, behavior 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 2014, Barisa 2015, Franco 2015, Jager 2009, Qudrat-Ullah 2013, Robalino-Lopez 2014). On the other hand, effects of employing decentralized energy systems have been investigated at regional and company levels (Hollmann 2006, Reddi 2013). Limitations of Life Cycle Assessment (LCA) were discussed, and simulation models were suggested to complement traditional methods such as LCA (Davis 2009, Miller 2012). It is notable that none of the papers in this category used DEMS.

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 2013). Some involved healthcare systems such as clinics and hospitals (Alexopoulos 2001, Petering 2015, Viana 2014), mobile healthcare system (Djanatliev 2013), rural healthcare system (Kumar 2014). Others investigated policy related issues at national level (Lin 2013, Lyons 2014). Papers for healthcare systems addressed efficiency issues by developing simulation models to optimize them. Also, the responsibility of the healthcare sector in the environment such as through generated emissions was considered and investigated using simulation studies (Fakhimi 2014).

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 2010, Hilty 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. Lovric (2013) developed an ABMS to effectively manage revenue

streams in public transportation system, by utilizing advanced analytics on data collected through smart cards.

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 2014).

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 realize 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 modeling. Limitations of lifecycle assessment (LCA) in manufacturing applications led to the development of supplementary or combined simulation models (Andersson 2012, Beukering 2001, Harun 2011, Johansson 2009, Lee 2012a, Lindskog 2011, Mani 2013, Paju 2010, Sproedt 2015, Stasinopoulos 2012). Plans and scenarios for reducing energy consumption, green house gas emissions, and material uses were investigated using simulation models (van Beukering 2001, Lindskog 2011, Solding 2006, Sproedt 2015). Meeting social needs during manufacturing activities have also been simulated along with other dimensions (Ajimotokan 2011, Lee 2012a). Beyond individual manufacturing systems, impact of government's regulations on sustainable manufacturing has been simulated (Dong 2012) and comparison between conventional bookstore selling and e-commerce has been studied using simulation models (Xu 2009). Among all the application areas, this category contains the most number of papers.

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 green house 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 modeled and studied (Maluleke 2013, O'Regan 2001, O'Regan 2006). SDMS was adopted for those studies in the South America and Ireland, but also for scenarios of international investment. Nageshwaraniyier (2011) used DEMS to optimize operation decisions during mining activities, utilizing real-time information collected from field

sensors and connected to a large information system such as Enterprise Resource Planning (ERP) system (Moon 2007).

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 modeling for sustainability. Current status, trends or challenges of certain technologies were explained and discussed (Axtell 2002, Bras 2009, Dietterich 2012, Gomes 2009, Kraines 2006, Sterman 2014a, Sterman 2014b). Literature reviews on different subjects were also conducted (Athanasiadis 2005, Zeng 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 analyzed by i) simulation techniques, ii) aspects of the triple bottom line model, and iii) application areas.

Social Behavior

As Faber (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 behavior in the context of sustainable development. Appropriateness of ABMS in studying social sustainability was discussed by Faber (2011) and Israel (2011). How public participation works in collective sustainable management was studied in ABMS model (Aquirre 2014). As illustrated in "Tragedy of the Commons" (Hardin 1968), the social dilemma was modeled utilizing ABMS where individual differences were maintained, then emerging patterns were observed and discussed (Sircova 2015). A particular social issue of poverty was examined under various fuel subsidy plans and cash payment plans (Smajgl 2013). It is notable that all five papers under this category adopted ABMS as their simulation method.

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 emphasized in order to leap the ultimate benefits from technological advances made such as in biofuels (Agusdinata 2012, Awudu 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 2008, Georgiadis 2010, Golroudbary 2015). Food supply chains have been simulated to meet the demands on food quality and associated sustainability issues (Krejci 2014, van der Vorst 2009). How to choose or design a desirable green supply chain has been studied with emission control in mind (Jaegler 2012, Rabe 2012, Tian 2014, Jain 2012, Jain 2013). Simulation models were considered particularly appropriate in handling flexibility in their analyses (Rabe 2012, van der Vorst 2009). Adoption of hybrid simulation models to accommodate different purposes and levels of detail for a same investigation has also been suggested (Jain 2012, Jain 2013).

Sustainable Development

This group of papers addressed sustainable development at national (Bockermann 2005, Moffatt 2001), groups of firms (Liu 2012, Romero 2014, Xu 2014) or individual corporate (Duran-Encalada 2012, Nikolaou 2015, Okada 2011, Su 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 toward achieving goals of sustainable development, especially by overcoming limitations of common models and tools that had been adopted for understanding sustainable development. Corporate behaviors and policies have been studied, which were influenced or influencing the environment, economic and other factors such as employment levels (Bockermann 2005, Duran-Encalada 2012, Liu 2012, Nikolaou 2015, Okada 2011, Su 2010). How a simulation model can be constructed using a Global Reporting Initiative report was illustrated by Duran-Encalada (2012).

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 2013, Maggi 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 2015b) adopted SDMS along with other techniques such as neural networks to investigate impacts of different scenarios in Tibet Autonomous Region in China.

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 2012). Also, traffic rules at road intersections have been simulated in order to optimize scheduling of vehicles' departure times (Jin 2012). Route optimization for emergency transportation (Kitagawa 2014) as well as university transportation (Upreti 2014) have been studied. Use of bicycles for sustainability and its impact on sustainability have been simulated and analyzed (Lee 2012). Advances in transportation technology such as cooperative adaptive cruise control system have been analyzed in simulation models in order to assess their potential contributions to sustainability (Ma 2012).

Urban & Community Planning

More than half of the world's population now live in cities and the proportion continues to grow (United Nations DESA 2014). This category contains papers addressing issues involved in urban planning along with a few papers on planning of unique communities. Cities that were growing as well as shrinking have been modeled in order to understand their future trajectories and corresponding influence on sustainability issues (Gaube 2013, Haase 2010). Specific issues such as noise control and optimization of traffic related sustainability issues have been studied (van Duin 2012, Katoshevski-Cavari 2011). Understanding urban residential development, sometimes with a focus on social segregation, has also been investigated (Steinhoffel 2012, Xu 2011, Xu 2012). Simulation studies have been conducted in communities different than urban settings, including less-favored rural areas in developing countries (Berger 2006), an Arctic community (Berman 2004), and a local community in Madagascar (Muller 2012). The impacts of development policy scenarios on such communities as well as interactions with locally unique factors have been investigated.

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 2012), to battery waste (Blumberga 2015), to electrical and electronic equipment waste (Shokohyar 2013, Mitsutaka 2010), to auto parts (Wang 2014, Mitsutaka 2010), and to paper (Georgiadis 2013). Simulation optimization was used to suggest best practices (Antmann 2012, Shokohyar 2013).

Water Resources

Water, one of the most important resources for sustaining human being, is unfortunately a limited asset. With the increasing 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 2013, Faezipour 2014, Giacomoni 2010, Mashhadi 2014, Sahin 2014, Sahin 2015, Susnik 2014, Xu 2002). Interactions among key entities such as customers, policy makers, water cycle components, food and security have been studied (Kanta 2010, Khan 2009, Susnik 2014).

4. Analyses

The number of publications on simulation modeling for sustainability is certainly on the rise as shown in Figure 1. Considering that the article includes only a portion of papers published until May 31, 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 modeling among domain experts, and better availability of simulation tools and computing power.

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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 utilizing simulation modeling, particularly Discrete-Event Modeling and Simulation (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.

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Figure 3 show distributions by dimensions of sustainable developed 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%).

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The most adopted simulation method was Agent-Based Modeling and Simulation (ABMS), but System Dynamics Modeling and Simulation (SDMS) was used almost equally as ABMS. Discrete-Event Modeling and Simulation (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 analyzed 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 the most frequently while DEMS is used the least frequently.

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There are various commercial as well as free software packages available to assist simulation modeling 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 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, 9 and 10. It is notable that 'Arena' has been the predominant software adopted for DEMS.

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5. 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 modeling, therefore, it is not surprising that simulation modeling made good contribution toward addressing sustainability issues. But it is also anticipated that simulation modeling 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 countries. Since sustainability truly concerns every nation and every person on earth, researchers in other countries will be utilizing 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 motivated to find additional research revenues. As computing powers and software technologies continue 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, optimization has been combined with simulation (Jin 2012, Kitagawa 2014, Krejci 2014, Schreinemachers 2011, Shokohyar 2013), and various machine learning techniques have also been used in conjunction with simulation (Sircova 2015, Smajgl 2013, Tian 2014, Zhang 2015b). It is expected that researchers find simulation modeling as useful techniques to complement other tools, or vice versa.

A 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 cleanly distinguish different simulation methods, hybrid simulation modeling can certainly help conceptually modeling different approaches 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.

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 2012, Boulonne 2010, Davis 2009, Shao 2010, van der Vorst 2009). Likewise, some research results are expected to contribute to advancing simulation techniques themselves, but motivated by addressing sustainability issues.

It would be useful to point out limitations of this article as well. 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 modeling 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 judgment call on which category was weighed more in the paper.

Perhaps the most well publicized 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 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 modeling, it was sometimes unfairly criticized 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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Zhou, X. & Kuhl, M.E., 2010. Design and Development of a Sustainability Toolkit for Simulation. In Winter Simulation Conference. pp. 1601–1612.

Application Areas	References
Agriculture, Aquaculture & Livestock	Balbi 2013a; Belcher 2004; BenDor 2009; de Kok 2015; Iwamura 2014; Li 2012; Martins 2014; Rebaudo 2013; Saysel 2002; Schouten 2014; Schreinemachers 2011
Construction	Ahn 2009; Ahn 2010; Gonzalez 2012; Hong 2011; Li 2010; Mallick 2014; Pearce 2010; Zhang 2014; Zhang 2015a
Ecosystem & Climate	Aubert 2015; Belem 2011; Gerst 2013; Learmonth 2011; Machado 2015; Mizuta 2001; Munthali 2014; Polhill 2013; Rogers 2012; Schreinemachers 2007
Energy	Aslani 2014; Barisa 2015; Batten 2009; Blumberga 2014; Colson 2014; Davis 2009; Franco 2015; Hollmann 2006; Jager 2009; Kiesling 2009; Miller 2012; Qudrat-Ullah 2013; Ramchurn 2011; Reddi 2013; Robalino-Lopez 2014; Shih 2014
Human Health	Alexopoulos 2001; Brailsford 2010; Djanatliev 2013; Fakhimi 2014; Kumar 2014; Lin 2013; Lyons 2014; McKnight 2013; Petering 2015; Viana 2014
Information Systems	Erdmann 2010; Hilty 2006; Lovric 2013; Sissa 2012
Land Use	Barnaud 2013; Bert 2011; Caillault 2013; Chen 2014; Filatova 2011; Le 2012; Miyasaka 2012; Murray-Rust 2014; Parker 2003; Ralha 2013; Villamor 2014
Manufacturing	Ajimotokan 2011; Andersson 2011; Andersson 2012; Barletta 2014; Beukering 2001; Boulonne 2010; Dong 2012; Harun 2011; Heilala 2008; Jain 2010; Johansson 2009; Kibira 2009; Lee 2012a; Lee 2014; Lindskog 2011; Mani 2013; Paju 2010; Shao 2010; Shao 2012; Solding 2005; Solding 2006; Sproedt 2015; Stasinopoulos 2012; Tan 2010; Thompson 2010; Wang 2014a; Widok 2011; Widok 2012; Wohlgemuth 2006; Xu 2009; Zhou 2010; Zhou 2011
Mining	Maluleke 2013; Nageshwarani 2011; O'Regan 2001; O'Regan 2006
Overview & Review	Athanasiadis 2005; Axtell 2002; Bras 2009; Dietterich 2012; Fakhimi 2013; Gomes 2009; Jayal 2010; Kraines 2006; Sterman 2014a; Sterman 2014b; Todorov 2009; Todorov 2011; Zeng 2011
Social Behavior	Aguirre 2014; Faber 2011; Israel 2011; Sircova 2015; Smajgl 2013

Supply Chain	Agusdinata 2012; Awudu 2012; Georgiadis 2008; Georgiadis 2010; Ghadimi 2014; Golroudbary 2015; Jaegler 2012; Jain 2012; Jain 2013; Krejci 2014; Liotta 2015; Rabe 2012; Tian 2014; van der Vorst 2009
Sustainable Development	Bockermann 2005; Duran-Encalada 2012; Liu 2012; Moffatt 2001; Nikolaou 2015; Okada 2011; Romero 2014; Su 2010; Xu 2014
Tourism	Balbi 2013b; Maggi 2011; Zhang 2015b
Transportation	DeLaurentis 2009; Egilmez 2012; Jin 2012; Kitagawa 2014; Kuhl 2009; Lee 2012b; Ma 2012; Upreti 2014
Urban & Community Planning	Berger 2006; Berman 2004; Gaube 2013; Haase 2010; Jin 2009; Katoshevski-Cavari 2011; Kuai 2015; Muller 2012; Piera 2015; Steinhoefel 2012; van Duin 2012; Xu 2011; Xu 2012
Waste, Recycling & Reuse	Antmann 2012; Blumberga 2015; Georgiadis 2013; Matsumoto 2010; Shokohyar 2013; Wang 2014b; Yang 2011
Water Resources	Dai 2013; Faezipour 2014; Giacomoni 2010; Kanta 2010; Khan 2009; Mashhadi 2014; Morales-Pinzon 2015; Ozik 2014; Sahin 2014; Sahin 2015; Susnik 2014; Winz 2008; Xu 2002

Table 1. Application Areas and Corresponding Papers
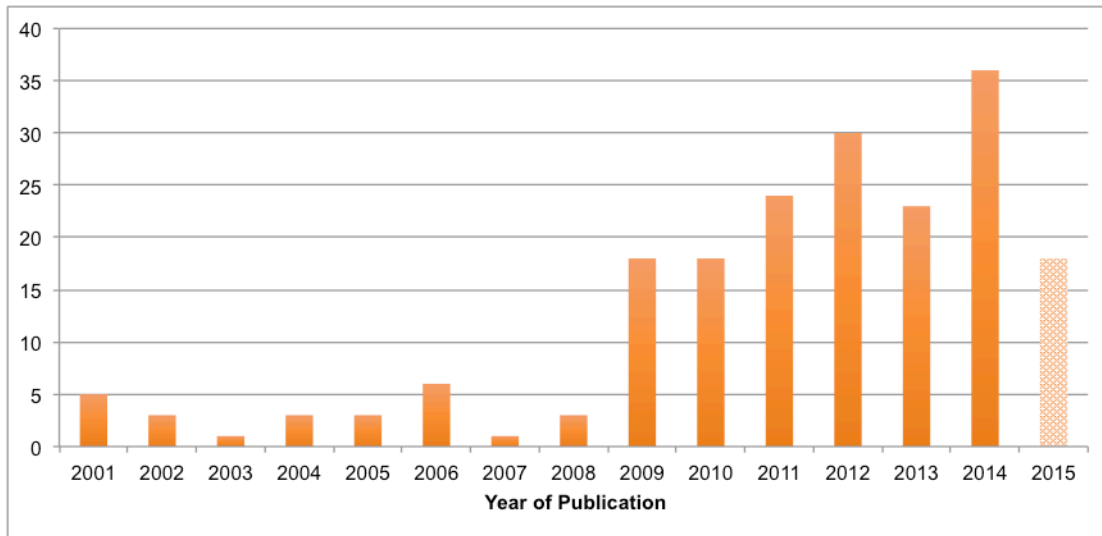
Figure 1. Number of Publication by Year
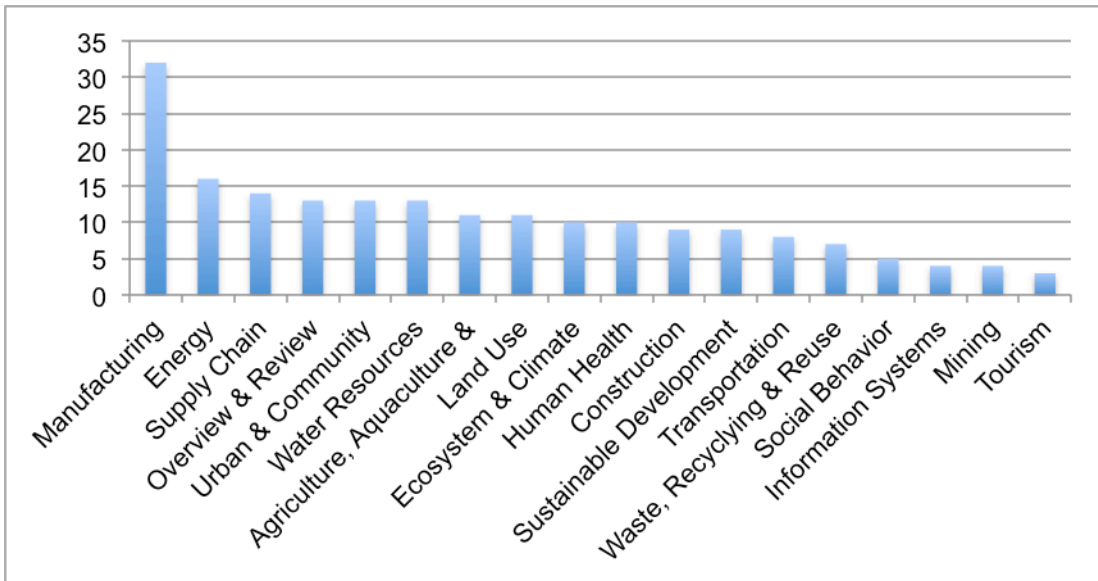
(a) Bar Chart
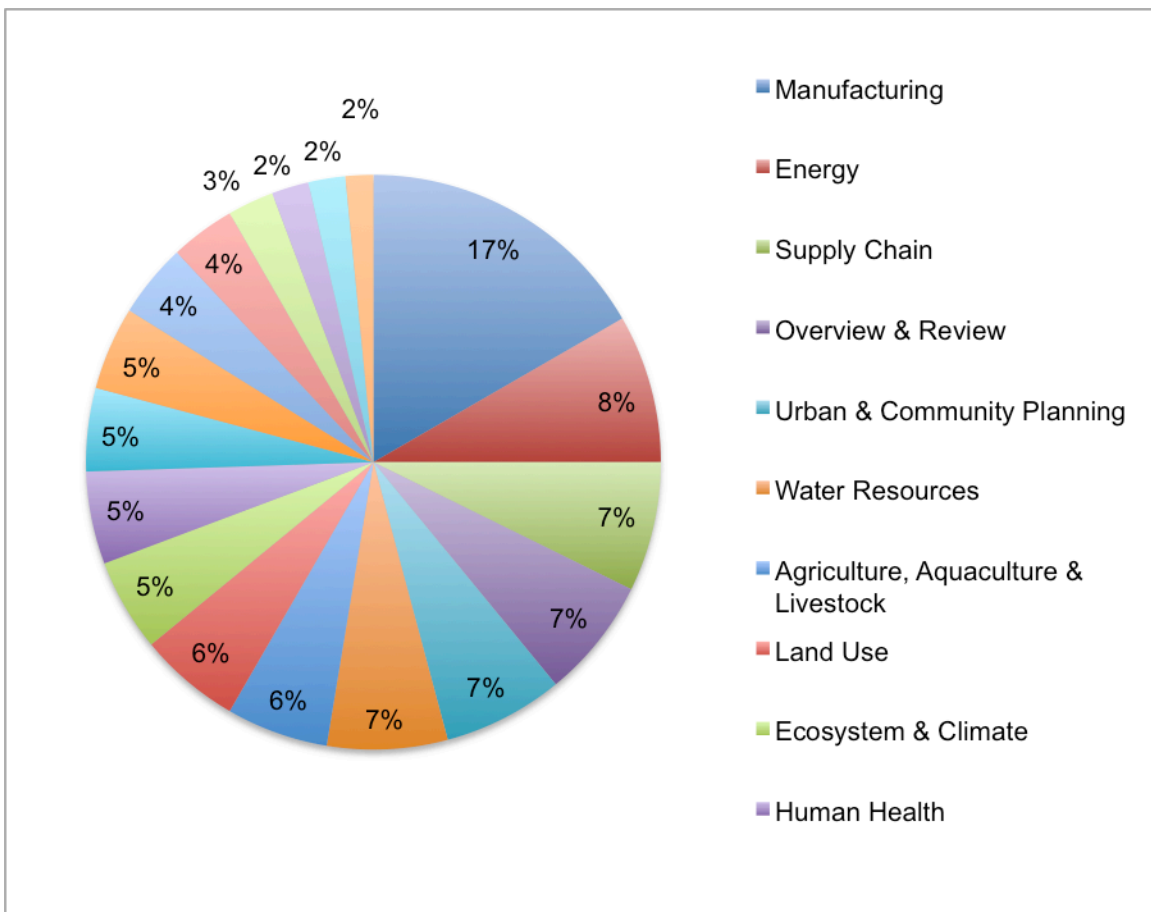
(a) Pie Chart

Figure 2. Number of Papers for Each Category
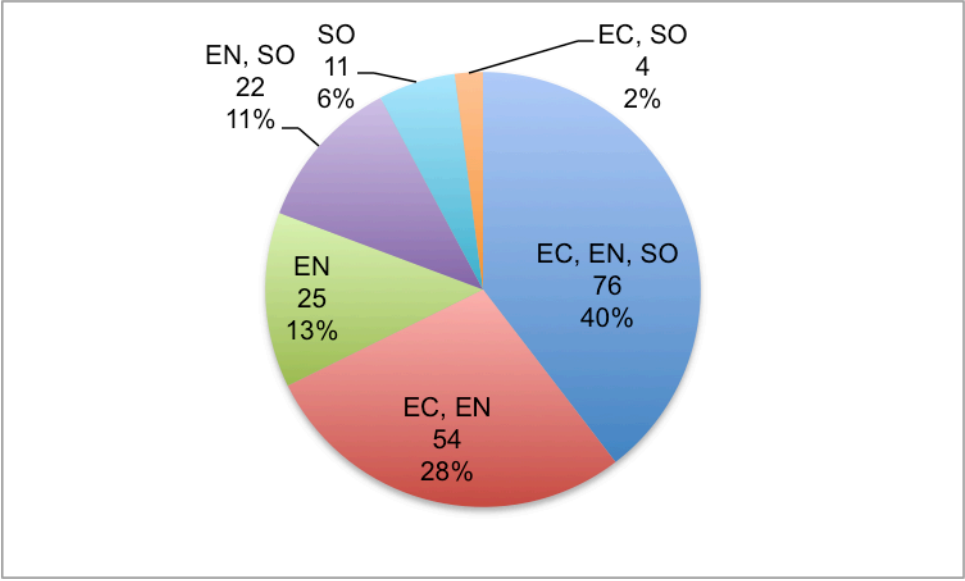
Figure 3. Coverage of Three Dimensions
(EC - economical, EN - environmental, SO - social)
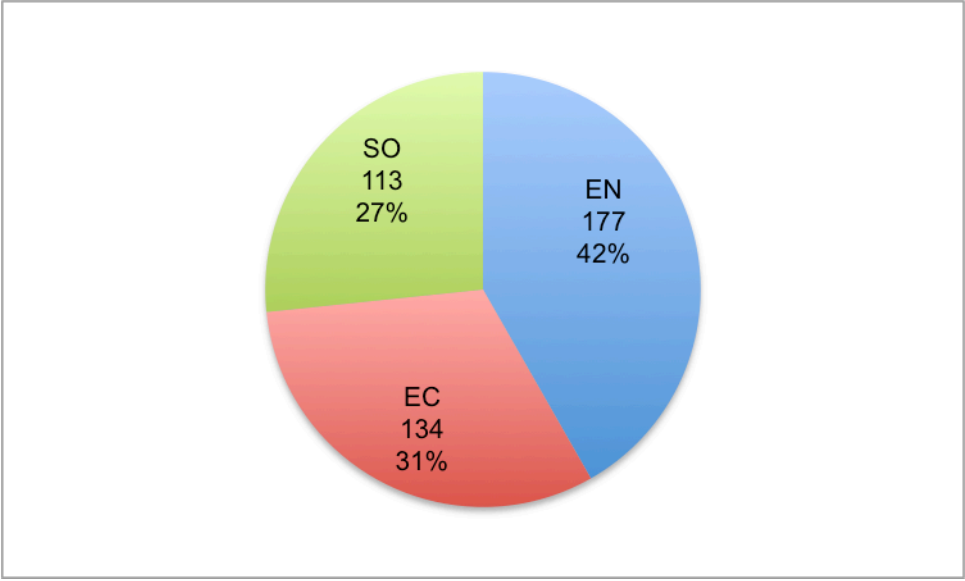
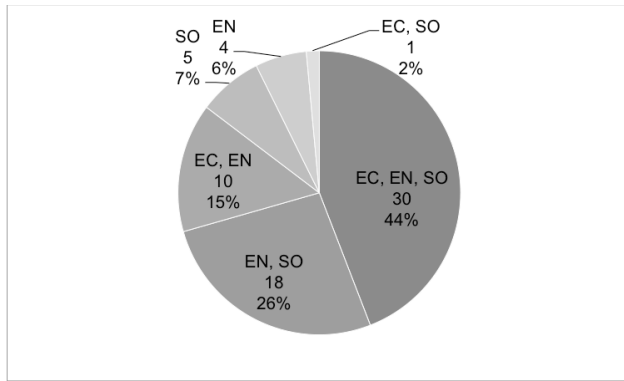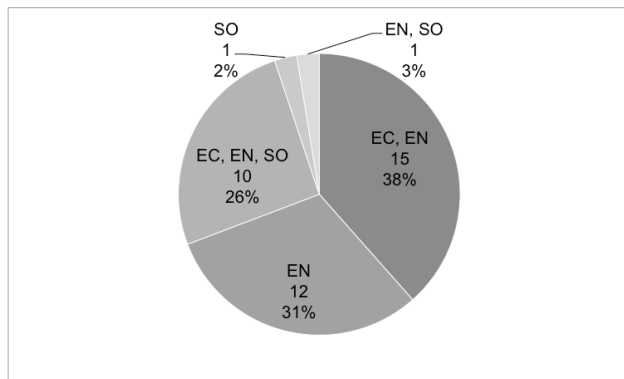Figure 4. Coverage of Three Dimensions
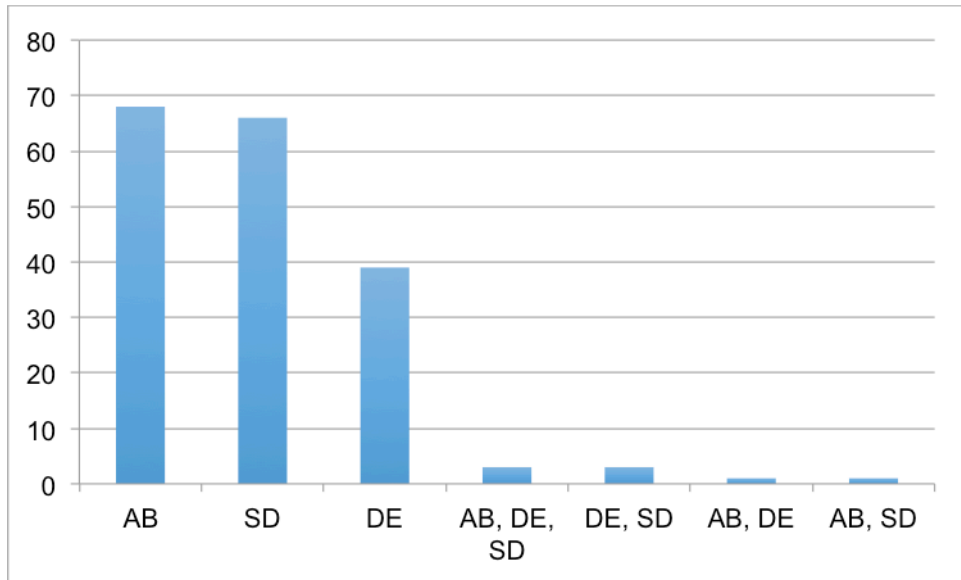
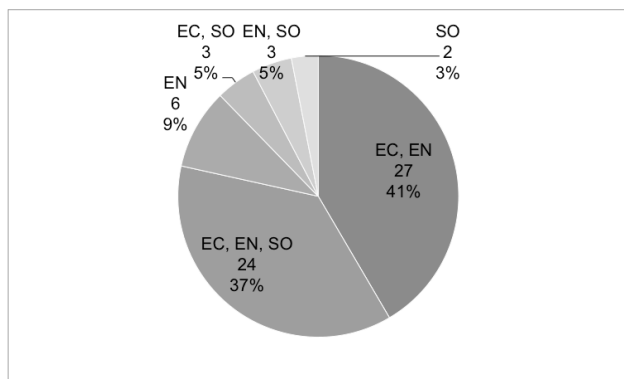(a) Bar Chart
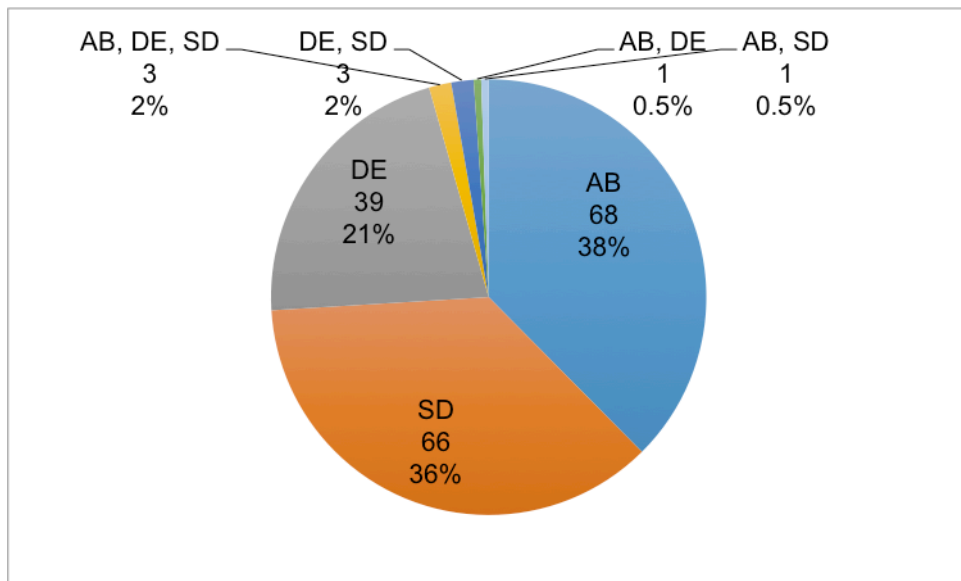
(b) Pie Chart

Figure 5. Adoption of Three Simulation Methods

(AB - Agent-Based Modeling and Simulation;
DE - Discrete Event Modeling and Simulation;
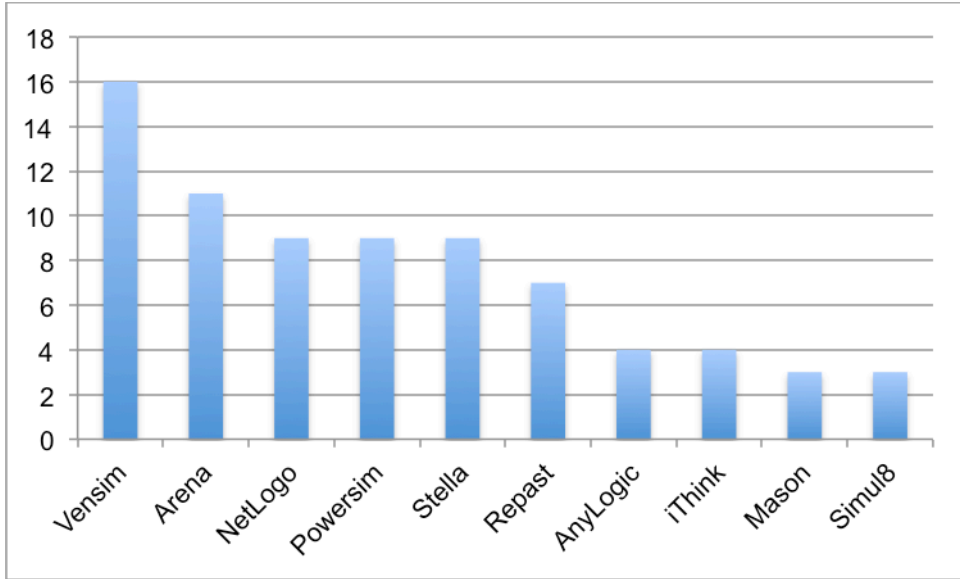SD - System Dynamics Modeling and Simulation)

(a) For papers adopting ABMS

(b) For papers adopting DEMS

(c) For papers adopting SDMS

Figure 6. Coverage of Three Dimensions by Each Group of Papers according to Simulation Types

(a) Bar Chart
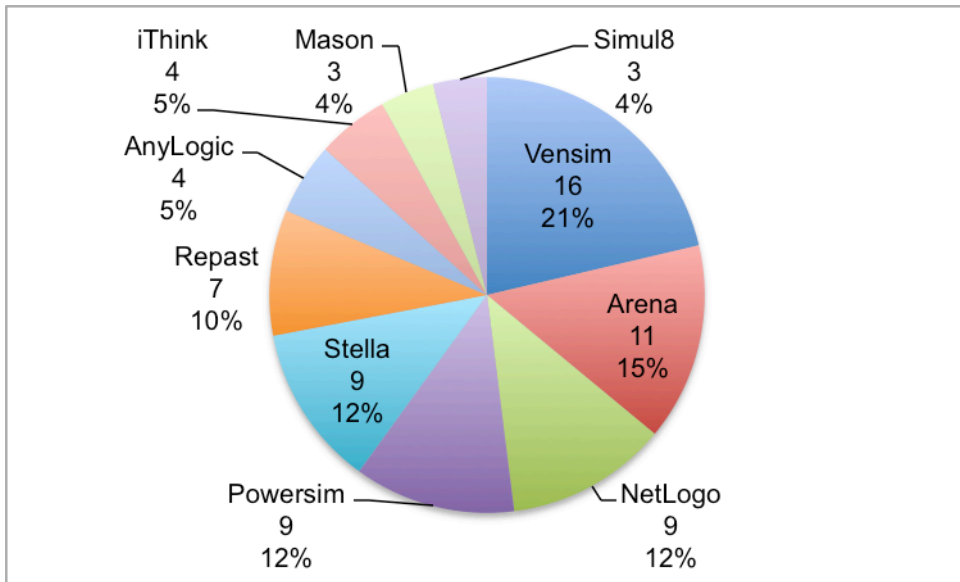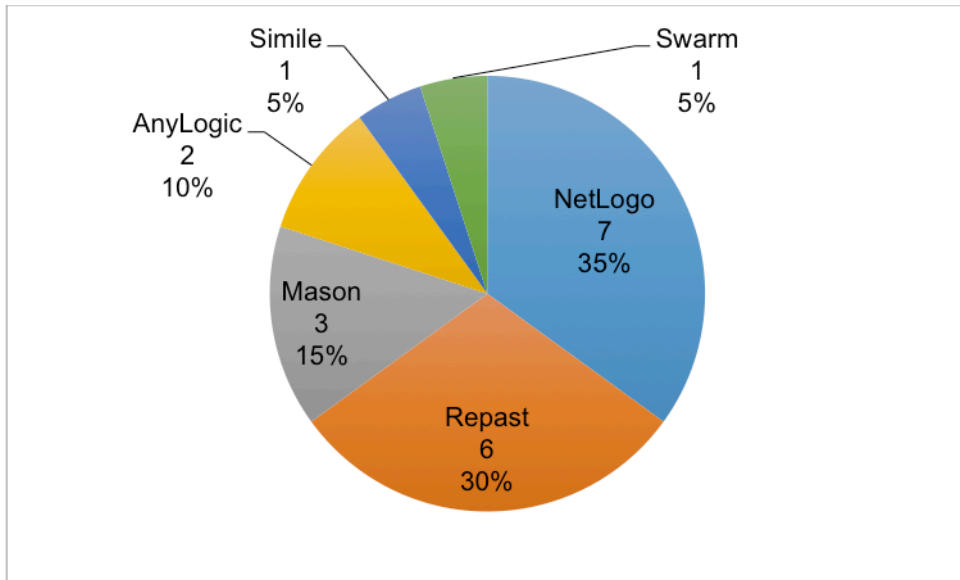

(b) Pie Chart

Figure 7. Uses of Software Packages

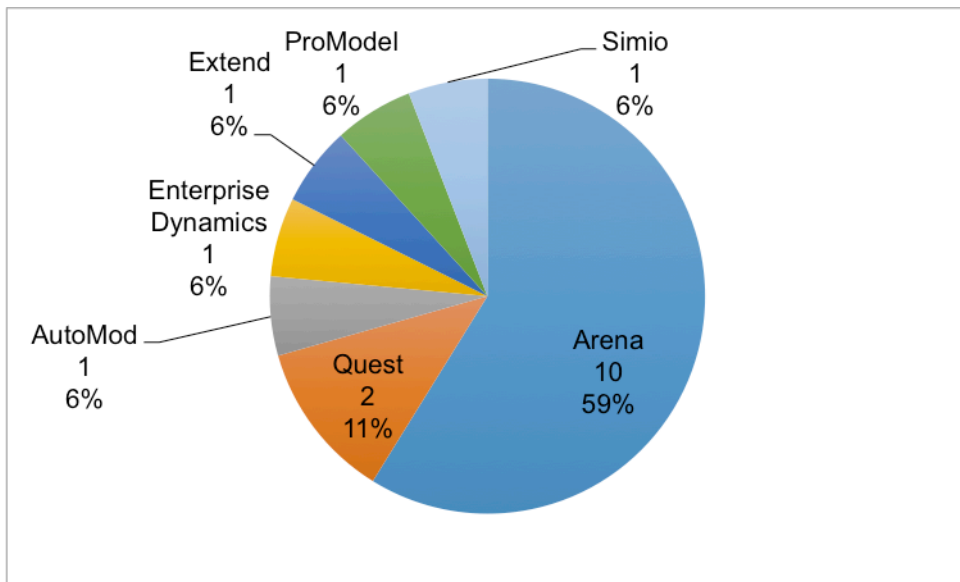Figure 8. Uses of Software Packages for Papers Adopting ABMS

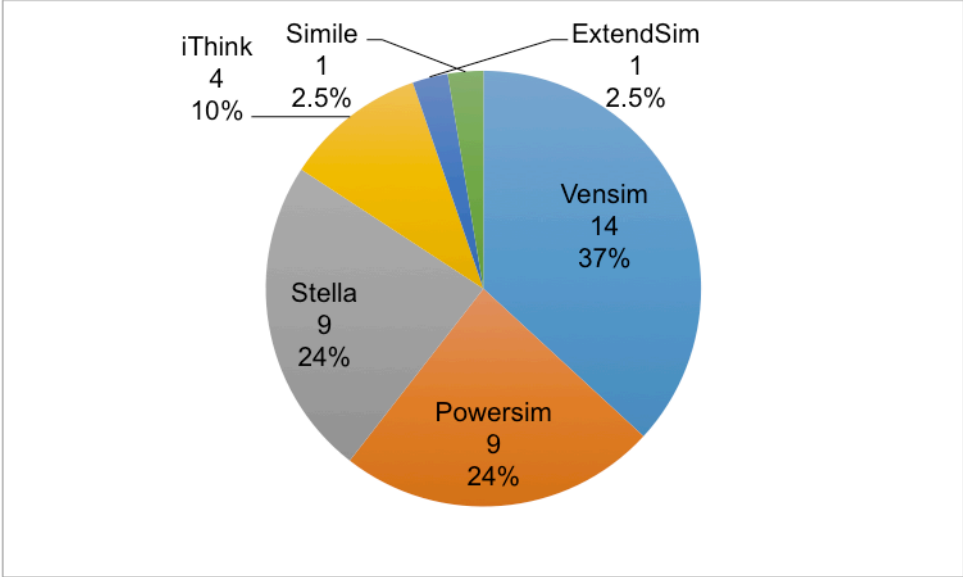Figure 9. Uses of Software Packages for Papers Adopting DEMS

Figure 10. Uses of Software Packages for Papers Adopting SDMS