8-30-2015

# Simulation Modeling for Sustainability: A Review of the Literature

Young B. Moon
*Syracuse University*, ybmoon@syr.edu



Recommended Citation
Moon, Young B. "Simulation Modelling for Sustainability: A Review of the Literature." International Journal of Sustainable Engineering (August 22, 2016): 1–18. doi:10.1080/19397038.2016.1220990.

# Simulation Modeling for Sustainability: A Review of the Literature

Young B. Moon

Department of Mechanical and Aerospace Engineering
Syracuse University
Syracuse, NY 13244

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.

Acknowledgement: Zhengyi Song and Mingtao Wu, doctoral students at Syracuse University provided assistant for the selection of papers reviewed and the development of categories for application areas.

## 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.

================
Table 1 Near Here
================

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.

================
Figure 1 Near Here
================

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.

================
Figure 2 Near Here
================

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%).

================
Figure 3 Near Here
================

================
Figure 4 Near Here
================

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.

================
Figure 5 Near Here
================

================
Figure 6 Near Here
================

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.

================
Figure 7 Near Here
================

================
Figure 8 Near Here
================

================
Figure 9 Near Here
================

================
Figure 10 Near Here
================

**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.

References

General References


Box, G.E.P., 1976. Science and Statistics. *Journal of the American Statistical Association*, 71(356), pp.791–799.

Department of Commerce, United States of America, 2015, "How does Commerce define Sustainable Manufacturing," available from: < http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp>.

Elkington, J., 1994. Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development. *California Management Review*, 36(2), pp. 90-100.

Gilbert, N., 2008. *Agent-Based Models*, Sage Publications.

Hardin, G., 1968. The Tragedy of the Commons. *Science*, 162, pp. 1243-1248.

INFORMS, 2014, " Simulation Software Survey — Simulation: a better reality?," available from: < https://www.informs.org/ORMS-Today/Public-Articles/October-Volume-40-Number-5/Simulation-Software-Survey-Simulation-a-better-reality>.

Law, A.M., 2014. *Simulation Modeling and Analysis*, McGraw-Hill.

Meadows, M.H. et al., 1972. *The Limits to Growth*, Potomac Associates.

Moon, Y.B., 2007. Enterprise Resource Planning (ERP): A Review of the Literature. *International Journal of Management and Enterprise Development*, 4(3), pp. 235-264.

Sterman, J.D., 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, McGraw-Hill/Irwin.

United Nations General Assembly (UNGA), 1987. "Report of the World Commission on Environment and Development: Our Common Future," available from: <http://www.un-documents.net/wced-ocf.htm>.

United Nations Department Economic and Social Affairs (DESA), 2014. "World's population increasingly urban with more than half living in urban areas," Available from: < http://www.un.org/en/development/desa/news/population/world-urbanization-prospects-2014.html >.

Reviewed References

Aguirre, R. & Nyerges, T., 2014. An Agent-Based Model of Public Participation in Sustainability Management. *Journal of Artificial Societies and Social Simulation*, 17(1), pp. 1–20.

Agusdinata, D.B. et al., 2012. Modeling Framework for Uncovering System Behaviors in Biofuels Supply Chain Network. In Third International Engineering Systems Symposium. Delft, Netherlands, pp. 1–12.

Ahn, C. et al., 2010. Lessons Learned from Utilizing Discrete-Event Simulation Modeling for Quantifying Construction Emissions in Pre-Planning Phase. In Winter Simulation Conference. pp. 3170–3176.

Ahn, C. et al., 2009. Sustainability Analysis of Earthmoving Operations. In Winter Simulation Conference. pp. 2605–2611.

Ajimotokan, H.A., 2011. Towards a rigorous equation-oriented technique for sustainable manufacturing safety programme. *Journal of Manufacturing Technology Management*, 23(1), pp. 76–86.

Alexopoulos, C. et al., 2001. A Discrete-Event Simulation Application for Clinics Serving the Poor. In Winter Simulation Conference. pp. 1386–1391.

Andersson, J., Skoogh, A. & Johansson, B., 2011. Environmental Activity Based Cost Using Discrete Event Simulation. In Winter Simulation Conference. pp. 891–902.

Andersson, J., Skoogh, A. & Johansson, B., 2012. Evaluation of Methods used for Life-Cycle Assessments in Discrete Event Simulation. In Winter Simulation Conference. pp. 1761–1772.

Antmann, E.D. et al., 2012. Simulation-based Optimization of Solid Waste Management and Recycling Programs. In Industrial and Systems Engineering Research Conference. pp. 1–10.

Aslani, A., Helo, P. & Naaranoja, M., 2014. Role of renewable energy policies in energy dependency in Finland: System dynamics approach. *Applied Energy*, 113, pp. 758–765.

Athanasiadis, I.N., 2005. A review of agent-based systems applied in environmental informatics. In Internatioal Congress on Modelling and Simulation Advances and Applications for Management and Decision Making. Melbourne, pp. 1574–1580.

Aubert, S., Muller, J.-P. & Ralihalizara, J., 2015. MIRANA: a socio-ecological model for assessing sustainability of community-based regulations. In D. A. Swayne et al., eds. International Congress on Environmental Modeling and Software. Ottawa, Canada, pp. 1–9.

Awudu, I. & Zhang, J., 2012. Uncertainties and sustainability concepts in biofuel supply chain management: A review. *Renewable and Sustainable Energy Reviews*, 16(2), pp.1359–1368.
Axtell, R.L., Andrews, C.J. & Small, M.J., 2002. Agent-Based Modeling and Industrial Ecology. *Journal of Industrial Ecology*, 5(4), pp. 10–13.

Balbi, S., Bhandari, S., et al., 2013. Multi-agent agro-economic simulation of irrigation water demand with climate services for climate change adaptation. *Italian Journal of Agronomy*, 8(3), pp. 175-185.

Balbi, S., Giupponi, C., et al., 2013. A spatial agent-based model for assessing strategies of adaptation to climate and tourism demand changes in an alpine tourism destination. *Environmental Modelling & Software*, 45, pp. 29–51.

Barisa, A. et al., 2015. Future biodiesel policy designs and consumption patterns in Latvia: a system dynamics model. *Journal of Cleaner Production*, 88, pp. 71–82.

Barletta, I. et al., 2014. Assessing a Proposal for an Energy-based Overall Equipment Effectiveness Indicator through Discrete Event Simulation. In Winter Simulation Conference. pp. 1096–1107.

Barnaud, C. et al., 2013. Spatial representations are not neutral: Lessons from a participatory agent-based modelling process in a land-use conflict. *Environmental Modelling & Software*, 45, pp. 150–159.

Batten, D.F., 2009. Fostering Industrial Symbiosis With Agent-Based Simulation and Participatory Modeling. *Journal of Industrial Ecology*, 13(2), pp. 197–213.

Belcher, K.W., Boehm, M.M. & Fulton, M.E., 2004. Agroecosystem sustainability: a system simulation model approach. *Agricultural Systems*, 79(2), pp. 225–241.

Belem, M. et al., 2011. CaTMAS: A multi-agent model for simulating the dynamics of carbon resources of West African villages. *Ecological Modelling*, 222(20-22), pp. 3651–3661.

BenDor, T., Scheffran, J. & Hannon, B., 2009. Ecological and economic sustainability in fishery management: A multi-agent model for understanding competition and cooperation. *Ecological Economics*, 68(4), pp. 1061–1073.

Berger, T., Schreinemachers, P. & Woelcke, J., 2006. Multi-agent simulation for the targeting of development policies in less-favored areas. *Agricultural Systems*, 88(1), pp. 28–43.

Berman, M. et al., 2004. Adaptation and Sustainability in a Small Arctic Community: Results of an Agent-Based Simulation Model. *Human Dimensions of the Arctic System*, 57(4), pp. 401–414.

Bert, F.E. et al., 2011. An agent based model to simulate structural and land use changes in agricultural systems of the argentine pampas. *Ecological Modelling*, 222(19), pp. 3486–3499.

Blumberga, A. et al., 2015. Dynamic modelling of a collection scheme of waste portable batteries for ecological and economic sustainability. *Journal of Cleaner Production*, 88, pp. 224–233.

Blumberga, A. et al., 2014. Sustainable development modelling for the energy sector. *Journal of Cleaner Production*, 63, pp. 134–142.

Bockermann, A. et al., 2005. Modelling sustainability. *Journal of Policy Modeling*, 27(2), pp. 189–210.

Boulonne, A. et al., 2010. Simulation Data Architecture for Sustainable Development. In Winter Simulation Conference. pp. 3435–3446.

Brailsford, S.C., Desai, S.M. & Viana, J., 2010. Towards the Holy Grail: Combining System Dynamics and Discrete-Event Simulation in Healthcare. In Winter Simulation Conference. pp. 2293–2303.

Bras, B., 2009. Sustainability and product life cycle management - issues and challenges. *International Journal of Product Lifecycle Management*, 4(1/2/3), pp. 23–48.

Caillault, S. et al., 2013. Influence of incentive networks on landscape changes: A simple agent-based simulation approach. *Environmental Modelling & Software*, 45, pp. 64–73.

Chen, H., Chang, Y.-C. & Chen, K.-C., 2014. Integrated wetland management: An analysis with group model building based on system dynamics model. *Journal of Environmental Management*, 146(C), pp. 309–319.

Colson, C.M. et al., 2014. Improving Sustainability of Hybrid Energy Systems Part II: Managing Multiple Objectives With a Multiagent System. *IEEE Transactions on Sustainable Energy*, 5(1), pp. 46–54.

Dai, S. et al., 2013. A system dynamics approach for water resources policy analysis in arid land: a model for Manas River Basin. *Journal of Arid Land*, 5(1), pp. 118–131.

Davis, C., Nikolić, I. & Dijkema, G.P.J., 2009. Integration of Life Cycle Assessment Into Agent-Based Modeling. *Journal of Industrial Ecology*, 13(2), pp. 306–325.

de Kok, J.-L., Engelen, G. & Maes, J., 2015. Reusability of model components for environmental simulation - Case studies for integrated coastal zone management. *Environmental Modelling & Software*, 68, pp. 42–54.

DeLaurentis, D.A. & Ayyalasomayajula, S., 2009. Exploring the Synergy Between Industrial Ecology and System of Systems to Understand Complexity. *Journal of Industrial Ecology*, 13(2), pp. 247–263.

Dietterich, T. et al., 2012. Machine Learning for Computational Sustainability. In International Green Computing Conference. pp. 1–6.

Djanatliev, A. & German, R., 2013. Prospective Healthcare Decision-Making by Combined System Dynamics, Discrete-Event and Agent-Based Simulation. In Winter Simulation Conference. pp. 270–281.

Dong, X. et al., 2012. Application of a system dynamics approach for assessment of the impact of regulations on cleaner production in the electroplating industry in China. *Journal of Cleaner Production*, 20(1), pp. 72–81.

Duran-Encalada, J.A. & Paucar-Caceres, A., 2012. A system dynamics sustainable business model for Petroleos Mexicanos (Pemex): case based on the Global Reporting Initiative. *Journal of the Operational Research Society*, 63(8), pp. 1065–1078.

Egilmez, G. & Tatari, O., 2012. A dynamic modeling approach to highway sustainability: Strategies to reduce overall impact. *Transportation Research Part A*, 46(7), pp. 1086–1096.

Erdmann, L. & Hilty, L.M., 2010. Scenario Analysis: Exploring the Macroeconomic Impacts of Information and Communication Technologies on Greenhouse Gas Emissions. *Journal of Industrial Ecology*, 14(5), pp. 826–843.

Faber, N.R. & Jorna, R.J., 2011. The Use of Multi-actor Systems for Studying Social Sustainability. In International Conference on Computer Supported Cooperative Work in Design. pp. 842–849.

Faezipour, M. & Ferreira, S., 2014. Assessing Water Sustainability Related to Hospitals Using System Dynamics Modeling. In Complex Adaptive Systems. Philadelphia, PA: Elsevier Masson SAS, pp. 27–32.

Fakhimi, M. et al., 2013. A Review of Literature in Modeling Approaches for Sustainable Development. In Winter Simulation Conference. pp. 282–290.

Fakhimi, M. et al., 2014. Hybrid Agent-Based and Discrete Event Simulation Approach for Sustainable Strategic Planning and Simulation Analytics. In Winter Simulation Conference. pp. 1573–1584.

Filatova, T., Voinov, A. & van der Veen, A., 2011. Land market mechanisms for preservation of space for coastal ecosystems: An agent-based analysis. *Environmental Modelling & Software*, 26(2), pp. 179–190.

Franco, C.J., Castaneda, M. & Dyner, I., 2015. Simulating the new British Electricity-Market Reform. *European Journal of Operational Research*, 245(1), pp. 273–285.

Gaube, V. & Remesch, A., 2013. Impact of urban planning on household's residential decisions: An agent-based simulation model for Vienna. *Environmental Modelling & Software*, 45, pp. 92–103.

Georgiadis, P., 2013. An integrated System Dynamics model for strategic capacity planning in closed-loop recycling networks: A dynamic analysis for the paper industry. *Simulation Modelling Practice and Theory*, 32, pp. 116–137.

Georgiadis, P. & Besiou, M., 2010. Environmental and economical sustainability of WEEE closed-loop supply chains with recycling: a system dynamics analysis. *International Journal of Advanced Manufacturing Technology*, 47(5-8), pp. 475–493.

Georgiadis, P. & Besiou, M., 2008. Sustainability in electrical and electronic equipment closed-loop supply chains: A System Dynamics approach. *Journal of Cleaner Production*, 16(15), pp. 1665–1678.

Gerst, M.D. et al., 2013. Agent-based modeling of climate policy: An introduction to the ENGAGE multi-level model framework. *Environmental Modelling & Software*, 44, pp. 62–75.

Ghadimi, P. & Heavey, C., 2014. MASOS: A Multi-Agent System Simulation Framework for Sustainable Supplier Evaluation and Order Allocation. In Winter Simulation Conference. pp. 1132–1143.

Giacomoni, M.H. & Zechman, E.M., 2010. A Complex Adaptive Systems Approach to Simulate Urban Water Resources Sustainability. In World Environmental and Water Resources Congress. pp. 2543–2549.

Golroudbary, S.R. & Zahraee, S.M., 2015. System dynamics model for optimizing the recycling and collection of waste material in a closed-loop supply chain. *Simulation Modelling Practice and Theory*, 53, pp. 88–102.

Gomes, C.P., 2009. Computational Sustainability. *The Bridge*, 39(4), pp. 5–13.

González, V. & Echaveguren, T., 2012. Exploring the environmental modeling of road construction operations using discrete-event simulation. *Automation in Construction*, 24, pp. 100–110.

Haase, D., Lautenbach, S. & Seppelt, R., 2010. Modeling and simulating residential mobility in a shrinking city using an agent-based approach. *Environmental Modelling & Software*, 25(10), pp. 1225–1240.

Harun, K. & Cheng, K., 2011. Life Cycle Simulation (LCS) Approach to the Manufacturing Process Design for Sustainable Manufacturing. In IEEE International Symposium on Assembly and Manufacturing. Tampere, pp. 1–8.

Heilala, J. et al., 2008. Simulation-based Sustainable Manufacturing System Design. In Winter Simulation Conference. pp. 1922–1930.

Hilty, L.M. et al., 2006. The relevance of information and communication technologies for environmental sustainability – A prospective simulation study. *Environmental Modelling & Software*, 21(11), pp. 1618–1629.

Hollmann, M., 2006. System Dynamics Modeling and Simulation of Distributed Generation of the Analysis of a Future Energy Supply. In International Conference of the System Dynamics Society. pp. 1–20.

Hong, Y. et al., 2011. Simulating the impacts of policy scenarios on the sustainability performance of infrastructure projects. *Automation in Construction*, 20(8), pp. 1060–1069.

Israel, N. & Wolf-Branigin, M., 2011. Nonlinearity in Social Service Evaluation: A Primer on Agent-based Modeling. *Social Work Research*, 35(1), pp. 20–24.

Iwamura, T. et al., 2014. Agent-based modeling of hunting and subsistence agriculture on indigenous lands: Understanding interactions between social and ecological systems. *Environmental Modelling & Software*, 58, pp. 109–127.

Jaegler, A. & Burlat, P., 2012. Carbon friendly supply chains: a simulation study of different scenarios. *Production Planning and Control*, 23(4), pp. 269–278.

Jager, T., Schmidt, S. & Karl, U., 2009. A System Dynamics Model for the German Electricity Market. In International Conference on Policy Modeling. Ottawa, Canada, pp. 1–14.

Jain, S. & Kibira, D., 2010. A Framework for Multi-Resolution Modeling of Sustainable Manufacturing. In Winter Simulation Conference. pp. 3423–3434.

Jain, S. & Siguroardottir, S., 2013. Multi-Resolution Modeling for Supply Chain Sustainability Analysis. In Winter Simulation Conference. pp. 1996–2007.

Jain, S., Lindskog, E. & Johansson, B., 2012. Supply Chain Carbon Footprint Tradeoffs using Simulation. In Winter Simulation Conference. pp. 3168–3179.

Jayal, A.D. et al., 2010. Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. *CIRP Journal of Manufacturing Science and Technology*, 2(3), pp. 144–152.

Jin, Q. et al., 2012. Multi-Agent Intersection Management for Connected Vehicles Using an Optimal Scheduling Approach. In International Conference on Connected Vehicles and Expo ICCVE. IEEE, pp. 185–190.

Jin, W., Xu, L. & Yang, Z., 2009. Modeling a policy making framework for urban sustainability: Incorporating system dynamics into the Ecological Footprint. *Ecological Economics*, 68(12), pp. 2938–2949.

Johansson, B. et al., 2009. Discrete Event Simulation to generate Requirements Specification for Sustainable Manufacturing Systems Design. In PerMIS. Gaithersburg, MD, pp. 38–42.

Kanta, L. & Zechman, E.M., 2010. An Agent-based Modeling Approach to Evaluate the Impact of Conservation Practices on Water Resources Sustainability. In World Environmental and Water Resources Congress. pp. 4253–4259.

Katoshevski-Cavari, R., Arentze, T.A. & Timmermans, H.J.P., 2011. Sustainable City-Plan Based on Planning Algorithm, Planners' Heuristics and Transportation Aspects. *Procedia - Social and Behavioral Sciences*, 20, pp. 131–139.

Khan, S., Yufeng, L. & Ahmad, A., 2009. Analysing complex behaviour of hydrological systems through a system dynamics approach. *Environmental Modelling & Software*, 24(12), pp. 1363–1372.

Kibira, D., Jain, S. & McLean, C.R., 2009. A System Dynamics Modeling Framework for Sustainable Manufacturing. In Systems Dynamics Society Conference. Albuquerque, NM, pp. 1–22.

Kiesling, E. et al., 2009. An Agent-Based Simulation Model for the Market Diffusion of a Second Generation Biofuel. In Winter Simulation Conference. pp. 1474–1481.

Kitagawa, H., Sato, K. & Takadama, K., 2014. Multiagent-based Sustainable Bus Route Optimization in Disaster. *Journal of Information Processing*, 22(2), pp. 235–242.

Kraines, S. & Wallace, D., 2006. Applying Agent-based Simulation in Industrial Ecology. *Journal of Industrial Ecology*, 10(1-2), pp. 15–18.

Krejci, C.C. & Beamon, B.M., 2014. Assessing Regional Farm-to-Institution Food Distribution Systems: An Agent-Based Approach. In Industrial and Systems Engineering Research Conference. pp. 1–10.

Kuai, P. et al., 2015. An application of system dynamics for evaluating planning alternatives to guide a green industrial transformation in a resource-based city. *Journal of Cleaner Production*, 104, pp. 403–412.

Kuhl, M.E. & Zhou, X., 2009. Sustainability Toolkit for Simulation-Based Logistics Decisions. In Winter Simulation Conference. pp. 1466–1473.

Kumar, D. & Kumar, D., 2014. Modelling Rural Healthcare Supply Chain in India using System Dynamics. In Global Congress on Manufacturing and Management. Elsevier B.V., pp. 2204–2212.

Le, Q.B., Seidl, R. & Scholz, R.W., 2012. Feedback loops and types of adaptation in the modelling of land-use decisions in an agent-based simulation. *Environmental Modelling & Software*, 27-28, pp. 83–96.

Learmonth, G. et al., 2011. *A practical approach to the complex problem of environmental sustainability: The UVa Bay Game*. *The Innovation Journal*, 16(1), pp. 1-9.

Lee, J.Y., Kang, H.S. & Noh, S.D., 2014. MAS$^2$: an integrated modeling and simulation-based life cycle evaluation approach for sustainable manufacturing. *Journal of Cleaner Production*, 66, pp. 146–163.

Lee, J.Y., Kang, H.S. & Noh, S.D., 2012. Simulation-based analysis for sustainability of manufacturing system. *International Journal of Precision Engineering and Manufacturing*, 13(7), pp. 1221–1230.

Lee, S. et al., 2012. Dynamic and multidimensional measurement of product-service system (PSS) sustainability: a triple bottom line (TBL)-based system dynamics approach. *Journal of Cleaner Production*, 32, pp. 173–182.

Li, F.J., Dong, S.C. & Li, F., 2012. A system dynamics model for analyzing the eco-agriculture system with policy recommendations. *Ecological Modelling*, 227, pp. 34–45.

Li, H.-X. & Lei, Z., 2010. Implementation of Discrete-Event Simulation (DES) in estimating & analyzing $CO_2$ emission during earthwork of building construction engineering. In IEEE International Conference on Industrial Engineering and Engineering Management. Xiamen, pp. 87–89.

Lin, F.-R. et al., 2013. Modeling an Agent-Based Healthcare Service System. In International Conference on Service Science and Innovation ICSSI. IEEE, pp. 67–74.

Lindskog, E. et al., 2011. A Method for Determining the Environmental Footprint of Industrial Products using Simulation. In Winter Simulation Conference. pp. 2136–2147.

Liotta, G., Kaihara, T. & Stecca, G., 2015. Optimization and Simulation of Collaborative Networks for Sustainable Production and Transportation. *IEEE Transactions on Industrial Informatics*, pp. 1–8.

Liu, Y. & Ye, H., 2012. The dynamic study on firm's environmental behavior and influencing factors: an adaptive agent-based modeling approach. *Journal of Cleaner Production*, 37, pp. 278–287.

Lovrić, M., Li, T. & Vervest, P., 2013. Sustainable revenue management: A smart card enabled agent-based modeling approach. *Decision Support Systems*, 54(4), pp. 1587–1601.

Lyons, G.J. & Duggan, J., 2014. System dynamics modelling to support policy analysis for sustainable health care. *Journal of Simulation*, 9(2), pp. 129–139.

Ma, J., Zhou, F. & Demetsky, M.J., 2012. Evaluating Mobility and Sustainability Benefits of Cooperative Adaptive Cruise Control Using Agent-based Modeling Approach. In IEEE Systems and Information Engineering Design Symposium. Charlottesville, VA, pp. 74–78.

Machado, R.R. et al., 2015. Evaluation of forest growth and carbon stock in forestry projects by system dynamics. *Journal of Cleaner Production*, 96, pp. 520–530.

Maggi, E., Stupino, F. & Fredella, F.L., 2011. A multi-agent simulation approach to sustainability in tourism development. In European Congress of the Regional Science Association International. Barcelona, Spain, pp. 1–17.

Mallick, R.B. et al., 2014. Use of system dynamics for proper conservation and recycling of aggregates for sustainable road construction. *Resources, Conservation and Recycling*, 86, pp. 61–73.

Maluleke, G. & Pretorius, L., 2013. A Systems Thinking Approach To Sustainable Manganese Mining: A Case For System Dynamics Modelling. In IEEE International Conference on Industrial Technology. Cape Town, South America, pp. 1–6.

Mani, M. et al., 2013. Simulation and analysis for sustainable product development. *International Journal of Life Cycle Assessment*, 18(5), pp. 1129–1136.

Martins, J.H. et al., 2014. A system dynamics model to support the management of artisanal dredge fisheries in the south coast of Portugal. *International Transactions in Operational Research*, pp. 1–24.

Mashhadi, A.A. et al., 2014. A Complex Adaptive Systems Approach To Simulate Interactions Among Water Resources, Decision-Makers, And Consumers And Assess Urban Water

Sustainability. In International Conference on Hydroinformatics. New York, NY, pp. 1–9.

Matsumoto, M., 2010. Development of a simulation model for reuse businesses and case studies in Japan. *Journal of Cleaner Production*, 18(13), pp. 1284–1299.

McKnight, U.S. & Finkel, M., 2013. A system dynamics model for the screening-level long-term assessment of human health risks at contaminated sites. *Environmental Modelling & Software*, 40, pp. 35–50.

Miller, S.A. et al., 2012. A Stochastic Approach to Model Dynamic Systems in Life Cycle Assessment. *Journal of Industrial Ecology*, 17(3), pp. 352–362.

Miyasaka, T. et al., 2012. An agent-based model for assessing effects of a Chinese PES programme on land-use change along with livelihood dynamics, and land degradation and restoration. In International Congress on Environmental Modeling and Software. Leipzig, Germany, pp. 1–8.

Mizuta, H. & Yamagata, Y., 2001. Agent-based Simulation and Greenhouse Gas Emissions Trading. In Winter Simulation Conference. pp. 535–540.

Moffatt, I. & Hanley, N., 2001. Modelling sustainable development: systems dynamic and input–ouput approaches. 16, pp. 545–557.

Morales-Pinzón, T. et al., 2015. Modelling for economic cost and environmental analysis of rainwater harvesting systems. *Journal of Cleaner Production*, 87, pp. 613–626.

Muller, J.-P. & Aubert, S., 2012. A Generic Model to Assess Sustainability of Resource Management Plans within Concurrent Regulatory Contexts. In Winter Simulation Conference. pp. 1098–1109.

Munthali, K.G. & Murayama, Y., 2014. Modeling deforestation in Dzalanyama Forest Reserve, Lilongwe, Malawi: a multi-agent simulation approach. *GeoJournal*, pp. 1–15.

Murray-Rust, D. et al., 2014. An open framework for agent based modelling of agricultural land use change. *Environmental Modelling & Software*, 61, pp. 19–38.

Nageshwaraniyer, S.S. et al., 2011. Simulation-Based Utility Assessment of Real-Time Information for Sustainable Mining Operations. In Winter Simulation Conference. pp. 871–882.

Nikolaou, I., Evangelinos, K. & Filho, W.L., 2015. A system dynamic approach for exploring the effects of climate change risks on firms' economic performance. *Journal of Cleaner Production*, 103, pp. 499–506.

O'Regan, B. & Moles, R., 2001. An insight into the system dynamics method: a case study in the dynamics of international minerals investment. 16, pp. 339–350.

O'Regan, B. & Moles, R., 2006. Using system dynamics to model the interaction between environmental and economic factors in the mining industry. *Journal of Cleaner Production*, 14(8), pp. 689–707.

Okada, I., 2011. An Agent-Based Model of Sustainable Corporate Social Responsibility Activities. *Journal of Artificial Societies and Social Simulation*, 14(3), pp. 1–29.

Ozik, J. et al., 2014. Simulating Water, Individuals, and Management using a Coupled and Distributed Approach. In Winter Simulation Conference. pp. 1120–1131.

Paju, M. et al., 2010. Framework and Indicators for a Sustainable Manufacturing Mapping Methodology. In Winter Simulation Conference. pp. 3411–3422.

Parker, D.C. et al., 2003. Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review. *Annals of the Association of American Geographers*, 93(2), pp. 314–337.

Pearce, A.R., Bernhardt, K.L.S. & Garvin, M.J., 2010. Sustainability and Socio-Enviro-Technical Systems: Modeling Total Cost of Ownership in Capital Facilities. In Winter Simulation Conference. pp. 3157–3169.

Petering, M.E.H. et al., 2015. Simulation analysis of hospital intensive care unit reimbursement policies from the triple bottom line perspective. *Journal of Simulation*, 9(2), pp. 86–98.

Piera, M.A., Buil, R. & Ginters, E., 2015. State space analysis for model plausibility validation in multi-agent system simulation of urban policies. *Journal of Simulation*, pp. 1–11.

Polhill, J.G., Gimona, A. & Gotts, N.M., 2013. Nonlinearities in biodiversity incentive schemes: A study using an integrated agent-based and metacommunity model. *Environmental Modelling & Software*, 45, pp. 74–91.

Qudrat-Ullah, H., 2013. Understanding the dynamics of electricity generation capacity in Canada: A system dynamics approach. *Energy*, 59, pp. 285–294.

Rabe, M. et al., 2012. An Approach for Increasing Flexibility in Green Supply Chains Driven by Simulation. In Winter Simulation Conference. pp. 3144–3155.

Ralha, C.G. et al., 2013. A multi-agent model system for land-use change simulation. *Environmental Modelling & Software*, 42, pp. 30–46.

Ramchurn, S.D. et al., 2011. Agent-based homeostatic control for green energy in the smart grid. *ACM Transactions on Intelligent Systems and Technology*, 2(4), pp. 1–28.

Rebaudo, F. & Dangles, O., 2013. An agent-based modeling framework for integrated pest management dissemination programs. *Environmental Modelling & Software*, 45, pp. 141–149.

Reddi, K.R. et al., 2013. System dynamics modelling of hybrid renewable energy systems and combined heating and power generator. *International Journal of Sustainable Engineering*, 6(1), pp. 31–47.

Robalino-López, A., Mena-Nieto, A. & García-Ramos, J.E., 2014. System dynamics modeling for renewable energy and $CO_2$ emissions: A case study of Ecuador. *Energy for Sustainable Development*, 20, pp. 11–20.

Rogers, J.D. et al., 2012. Modelling scale and variability in human-environmental interactions in Inner Asia. *Ecological Modelling*, 241, pp. 5–14.

Romero, E. & Ruiz, M.C., 2014. Proposal of an agent-based analytical model to convert industrial areas in industrial eco-systems. *Science of the Total Environment*, 468-469, pp.394–405.

Sahin, O. et al., 2014. Paradigm shift to enhanced water supply planning through augmented grids, scarcity pricing and adaptive factory water: A system dynamics approach. *Environmental Modelling & Software*, pp. 1–14.

Sahin, O., Stewart, R.A. & Porter, M.G., 2015. Water security through scarcity pricing and reverse osmosis: a system dynamics approach. *Journal of Cleaner Production*, 88, pp. 160–171.

Saysel, A.K., Barlas, Y. & Yenigün, O., 2002. Environmental sustainability in an agricultural development project: a system dynamics approach. *Journal of Environmental Management*, 64(3), pp. 247–260.

Schouten, M., Verwaart, T. & Heijman, W., 2014. Comparing two sensitivity analysis approaches for two scenarios with a spatially explicit rural agent-based model. *Environmental Modelling & Software*, 54, pp. 196–210.

Schreinemachers, P. & Berger, T., 2011. An agent-based simulation model of human-environment interactions in agricultural systems. *Environmental Modelling & Software*, 26(7), pp. 845–859.

Schreinemachers, P., Berger, T. & Aune, J.B., 2007. Simulating soil fertility and poverty dynamics in Uganda: A bio-economic multi-agent systems approach. *Ecological Economics*, 64(2), pp. 387–401.

Shao, G. et al., 2012. A Framework for Interoperable Sustainable Manufacturing Process Analysis Applications Development. In Winter Simulation Conference. pp. 3069–3079.

Shao, G., Bengtsson, N. & Johansson, B., 2010. Interoperability for Simulation of Sustainable Manufacturing. In SCS. pp. 1–8.

Shih, Y.-H. & Tseng, C.-H., 2014. Cost-benefit analysis of sustainable energy development using life-cycle co-benefits assessment and the system dynamics approach. *Applied Energy*, 119, pp. 57–66.

Shokohyar, S. & Mansour, S., 2013. Simulation-based optimisation of a sustainable recovery network for Waste from Electrical and Electronic Equipment (WEEE). *International Journal of Computer Integrated Manufacturing*, 26(6), pp. 487–503.

Sircova, A. et al., 2015. Simulating Irrational Human Behavior to Prevent Resource Depletion C.-Y. Xia, ed. *PLOS ONE*, 10(3), pp. 1–20.

Sissa, G., 2012. An Agent Based approach for sustainable ICT services toward environmental sustainability. In IEEE International Conference on Digital Ecosystems Technologies. Campione, Italy, pp. 1–6.

Smajgl, A. & Bohensky, E., 2013. Behaviour and space in agent-based modelling: Poverty patterns in East Kalimantan, Indonesia. *Environmental Modelling & Software*, 45, pp. 8–14.

Solding, P. & Petku, D., 2005. Applying Energy Aspects on Simulation of Energy Intensive Production Systems. In Winter Simulation Conference. pp. 1428–1432.

Solding, P. & Thollander, P., 2006. Increased Energy Efficiency in a Swedish Iron Foundry Through Use of Discrete Event Simulation. In Winter Simulation Conference. pp. 1971–1976.

Sproedt, A. et al., 2015. A simulation-based decision support for eco-efficiency improvements in production systems. *Journal of Cleaner Production*, 105, pp. 389–405.

Stasinopoulos, P. et al., 2012. A system dynamics approach in LCA to account for temporal effects—a consequential energy LCI of car body-in-whites. *International Journal of Life Cycle Assessment*, 17(2), pp. 199–207.

Steinhoefel, J. et al., 2012. Investigation of Cognitive Neighborhoodsize by Agent-Based Simulation. In European Conference on Modelling and Simulation. pp. 1–7.

Sterman, J., 2014a. Interactive web-based simulations for strategy and sustainability: The MIT Sloan LearningEdge management flight simulators, Part II. *System Dynamics Review*, 30(3), pp. 206–231.

Sterman, J., 2014b. Interactive web-based simulations for strategy and sustainability: The MIT Sloan *LearningEdge* management flight simulators, Part I. *System Dynamics Review*, 30(1-2), pp. 89–121.

Su, Y. & Al-Hakim, L., 2010. System Dynamics Modeling for Green IT Strategies. In International Conference on Challenges in Environmental Science and Computer Engineering. IEEE, pp. 504–507.

Susnik, J. et al., 2013. Integrated modelling of a coupled water-agricultural system using system dynamics. *Journal of Water and Climate Change*, 4(3), pp. 209–231.

Tan, K.S., Daud Ahmed, M. & Sundaram, D., 2010. Sustainable enterprise modelling and simulation in a warehousing context J. Barjis, ed. *Business Process Management Journal*, 16(5), pp. 871–886.

Thompson, J.P. & Cavaleri, S., 2010. Dynamic Knowledge, Organizational Growth, and Sustainability. *International Studies of Management and Organization*, 40(3), pp. 50–60.

Tian, Y., Govindan, K. & Zhu, Q., 2014. A system dynamics model based on evolutionary game theory for green supply chain management diffusion among Chinese manufacturers. *Journal of Cleaner Production*, 80, pp. 96–105.

Todorov, V. & Marinova, D., 2011. Modelling sustainability. *Mathematics and Computers in Simulation*, 81(7), pp. 1397–1408.

Todorov, V.I. & Marinova, D., 2009. Models of Sustainability. In R. S. Anderssen, R. D. Braddock, & L. T. H. Newham, eds. MODSIM International Congress on Modelling and Simulation. Cairns, pp. 1216–1222.

Upreti, G. et al., 2014. Increasing transport efficiency using simulation modeling in a dynamic modeling approach. *Journal of Cleaner Production*, 85, pp. 433–441.

van Beukering, P.J.H. & Janssen, M.A., 2001. A Dynamic Integrated Analysis of Truck Tires in Western Europe. *Journal of Industrial Ecology*, 4(2), pp. 93–115.

van der Vorst, J., Tromp, S.-O. & Zee, D.-J.V.D., 2009. Simulation modelling for food supply chain redesign; integrated decision making on product quality, sustainability and logistics. *International Journal of Production Research*, 47(23), pp. 6611–6631.

van Duin, J.H.R. & van der Heijden, R.E.C.M., 2012. Towards governance on noise between municipality and terminal operator by the use of simulation modelling. *Journal of Computational Science*, 3(4), pp. 216–227.

Viana, J., 2014. Reflections on Two Approaches to Hybrid Simulation in Healthcare. In Winter Simulation Conference. pp. 1585–1596.

Villamor, G.B. et al., 2014. Biodiversity in rubber agroforests, carbon emissions, and rural livelihoods: An agent-based model of land-use dynamics in lowland Sumatra. *Environmental Modelling & Software*, 61, pp. 151–165.

Wang, B., Brême, S. & Moon, Y.B., 2014. Hybrid modeling and simulation for complementing Lifecycle Assessment. *Computers & Industrial Engineering*, 69, pp. 77–88.

Wang, Y. et al., 2014. Impact of subsidy policies on recycling and remanufacturing using system dynamics methodology: a case of auto parts in China. *Journal of Cleaner Production*, 74, pp. 161–171.

Widok, A.H. et al., 2012. Achieving Sustainability through a Combination of LCA and DES Integrated in a Simulation Software for Production Processes. In Winter Simulation Conference. pp. 1749–1760.

Widok, A.H., Page, B. & Wohlgemuth, V., 2011. Combining Sustainability Criteria with Discrete Event Simulation. In Winter Simulation Conference. pp. 859–870.

Winz, I., Brierley, G. & Trowsdale, S., 2009. The Use of System Dynamics Simulation in Water Resources Management. *Water Resources Management*, 23(7), pp. 1301–1323.

Wohlgemuth, V., Page, B. & Kreutzer, W., 2006. Combining discrete event simulation and material flow analysis in a component-based approach to industrial environmental protection. *Environmental Modelling & Software*, 21(11), pp. 1607–1617.

Xu, J., Deng, Y. & Yao, L., 2014. Sustainable development-oriented industrial restructuring modeling and analysis: a case study in Leshan. *Clean Technologies and Environmental Policy*, 16(2), pp. 267–279.

Xu, M. et al., 2009. A Dynamic Agent-Based Analysis for the Environmental Impacts of Conventional and Novel Book Retailing. *Environmental Science & Technology*, 43(8), pp. 2851–2857.

Xu, Z. & Coors, V., 2011. Application of System Dynamics, GIS and 3D Visualization in a Study of Residential Sustainability. In Computational Science and Its Applications - ICCSA. pp. 300–314.

Xu, Z. & Coors, V., 2012. Combining system dynamics model, GIS and 3D visualization in sustainability assessment of urban residential development. *Building and Environment*, 47, pp. 272–287.

Xu, Z.X. et al., 2002. Sustainability Analysis for Yellow River Water Resources Using the System Dynamics Approach. *Water Resources Management*, 16, pp. 239–261.

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

Zeng, Y. et al., 2011. A Review on Optimization Modeling of Energy Systems Planning and GHG Emission Mitigation under Uncertainty. *Energies*, 4(12), pp. 1624–1656.

Zhang, H., 2015. Simulation-Based Estimation of Fuel Consumption and Emissions of Asphalt Paving Operations. *Journal of Computing in Civil Engineering*, 29(2), pp. 1–13.

Zhang, J., Ji, M. & Zhang, Y., 2015. Tourism sustainability in Tibet – Forward planning using a systems approach. *Ecological Indicators*, 56, pp. 218–228.

Zhang, X. et al., 2014. A prototype system dynamic model for assessing the sustainability of construction projects. *International Journal of Project Management*, 32(1), pp. 66–76.

Zhou, X. & Kuhl, M.E., 2011. A Sustainability Toolkit for Simulation: Recent Developments and Future Capabilities. In Winter Simulation Conference. pp. 850–858.

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

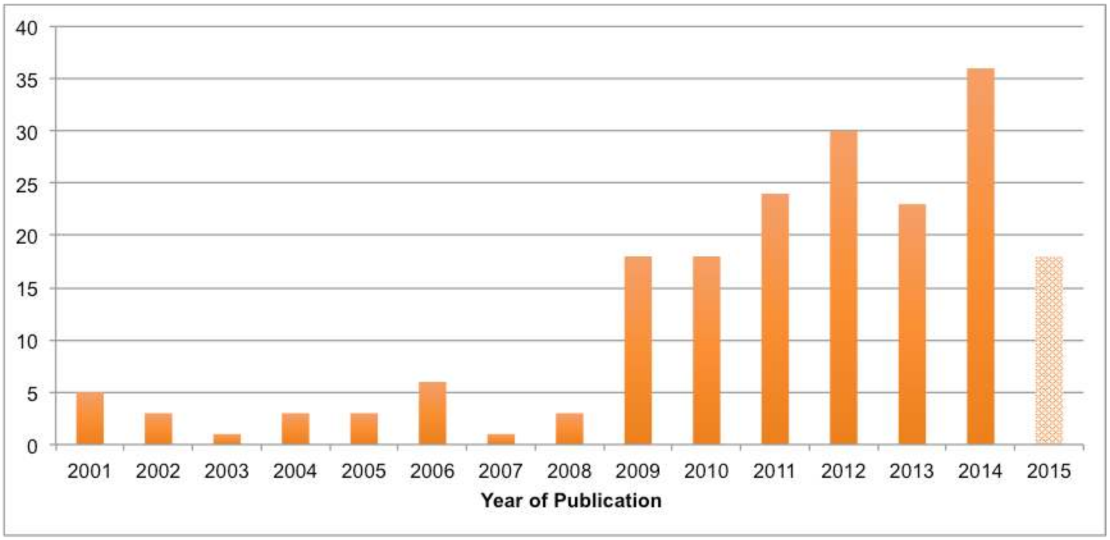
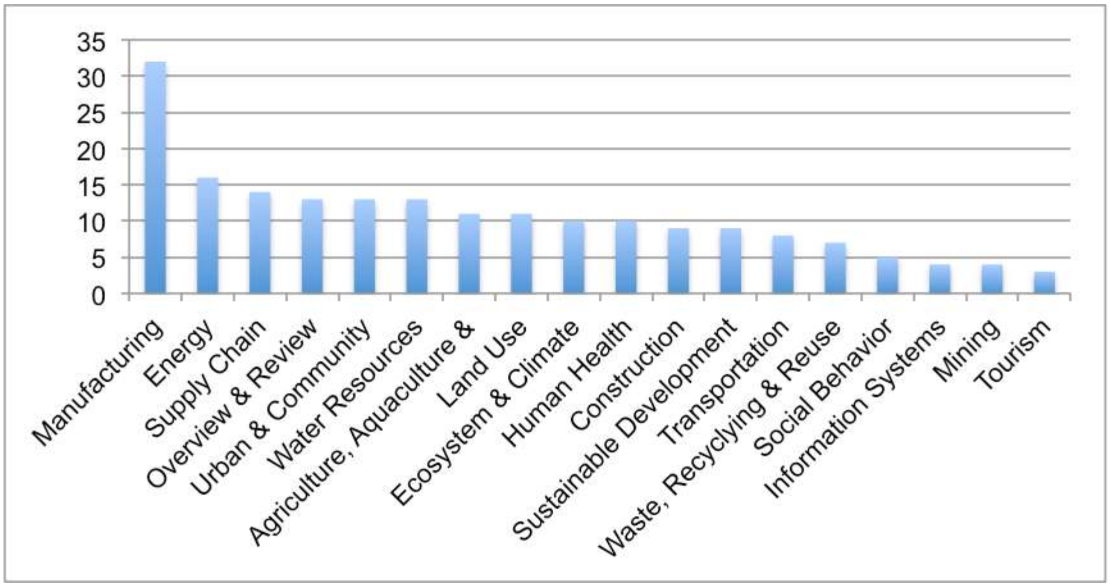
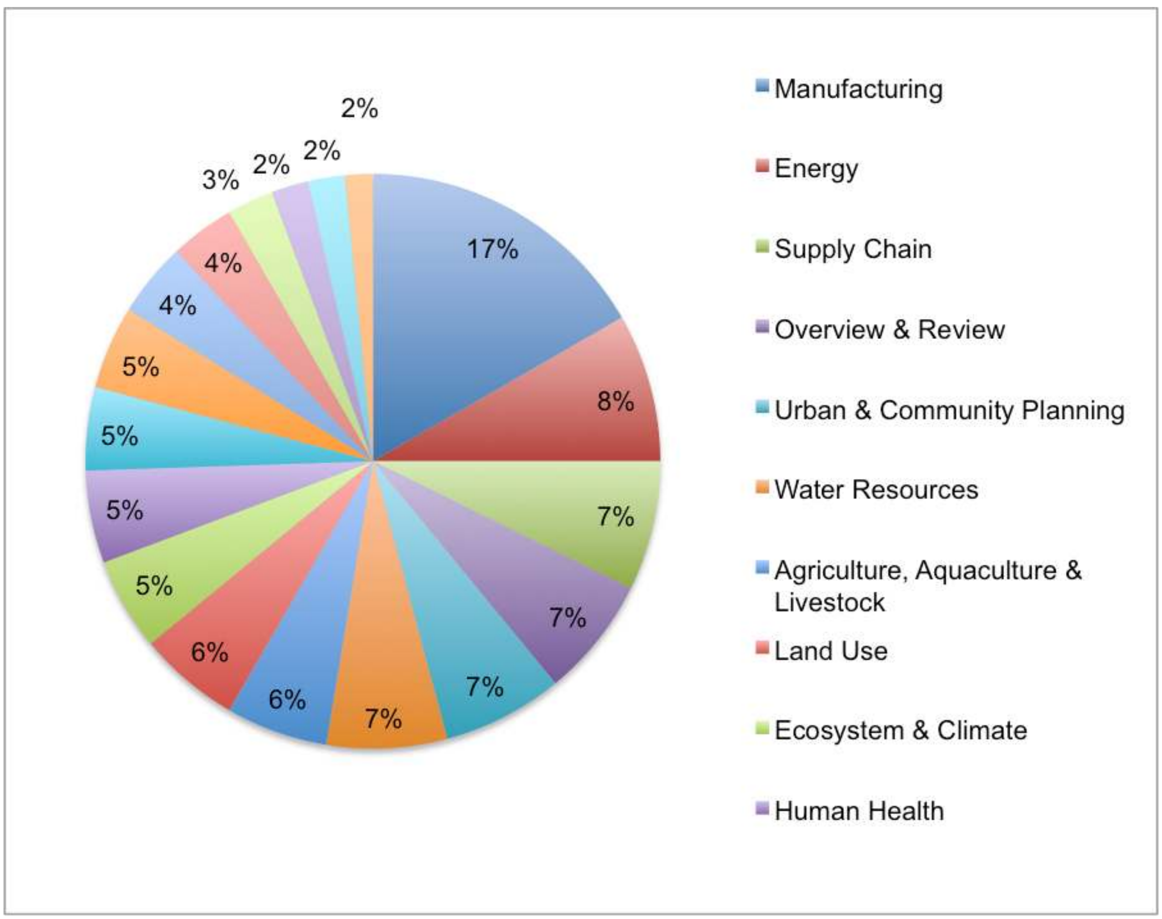



Figure 1. Number of Publication by Year




(a) Bar Chart




(a) Pie Chart

Figure 2. Number of Papers for Each Category

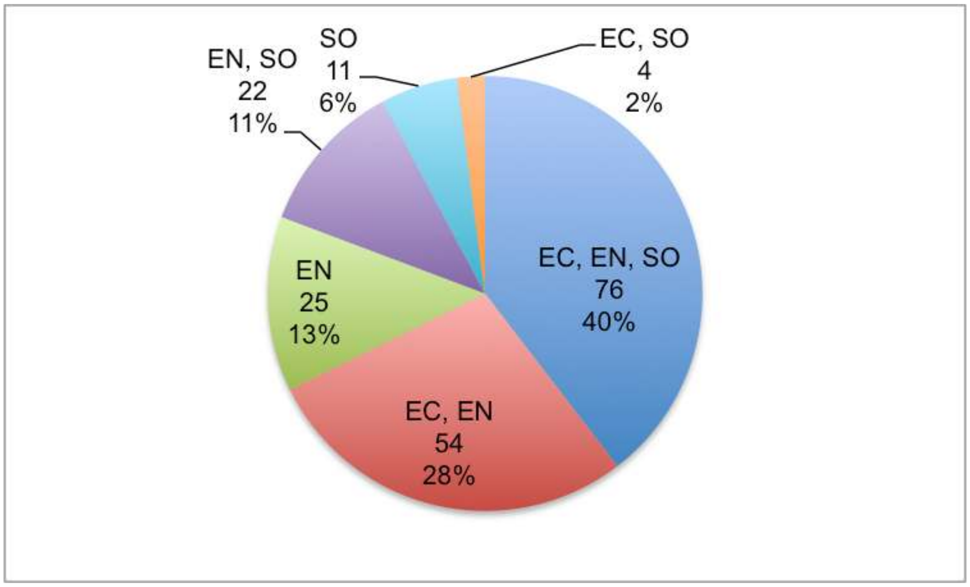



Figure 3. Coverage of Three Dimensions
(EC - economical, EN - environmental, SO - social)

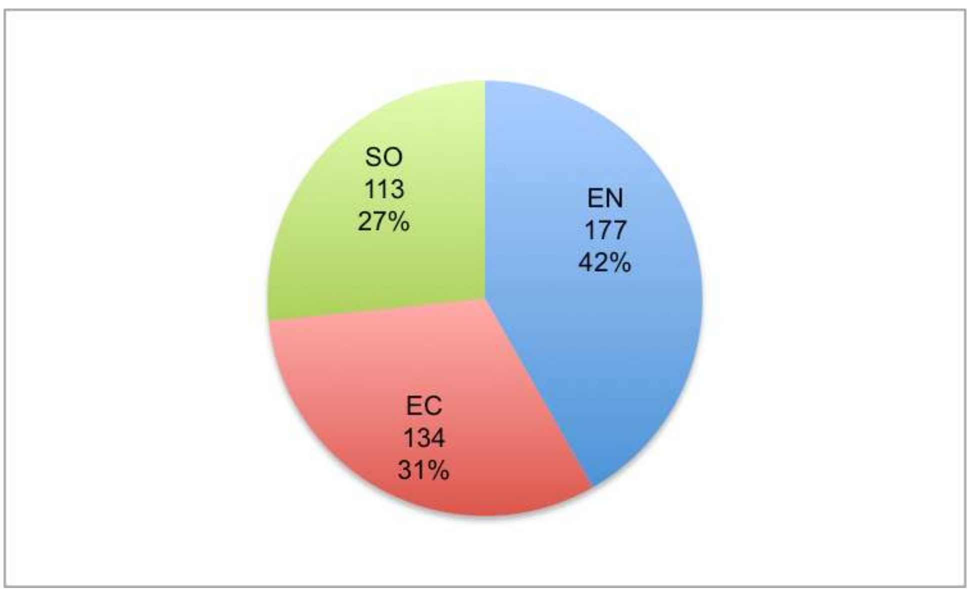
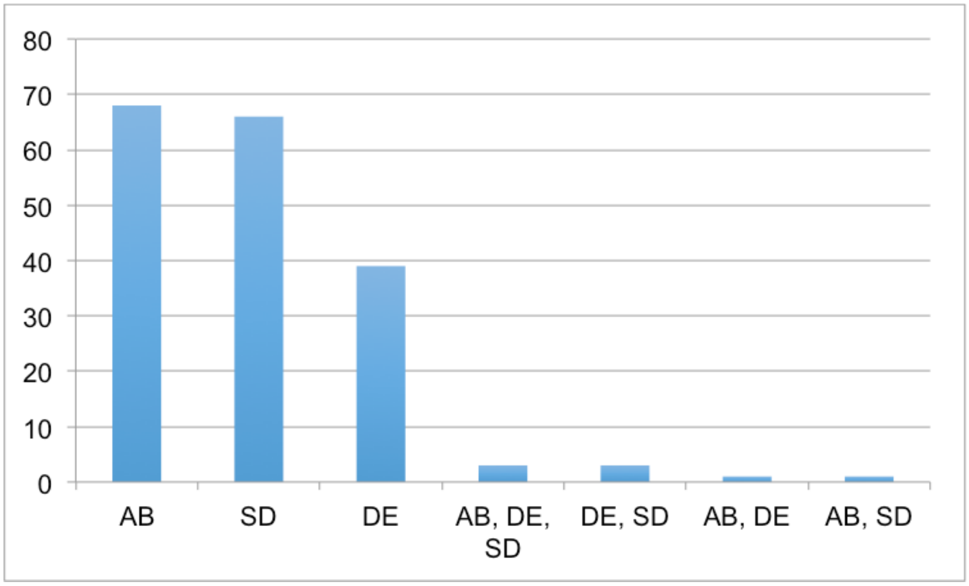
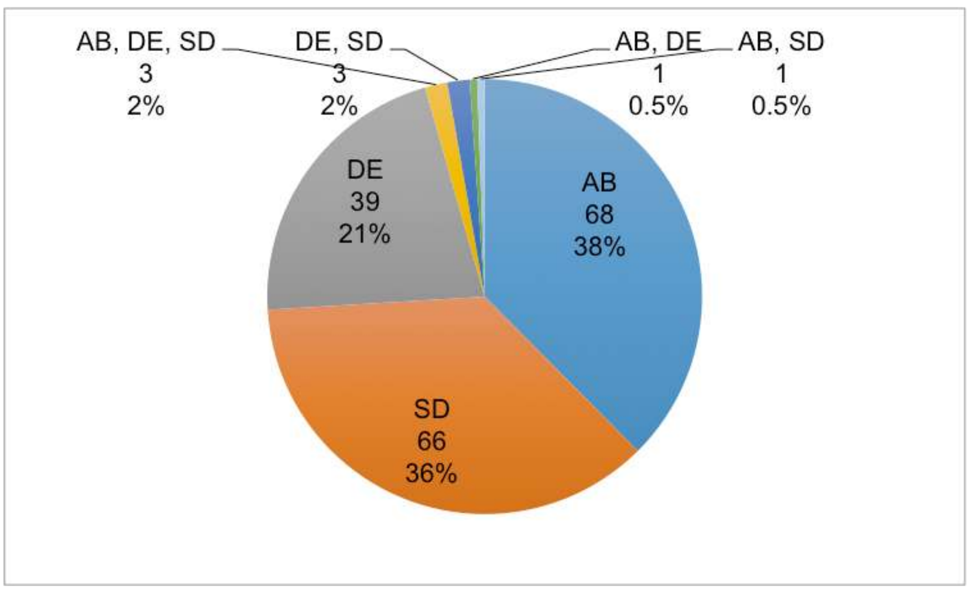



Figure 4. Coverage of Three Dimensions



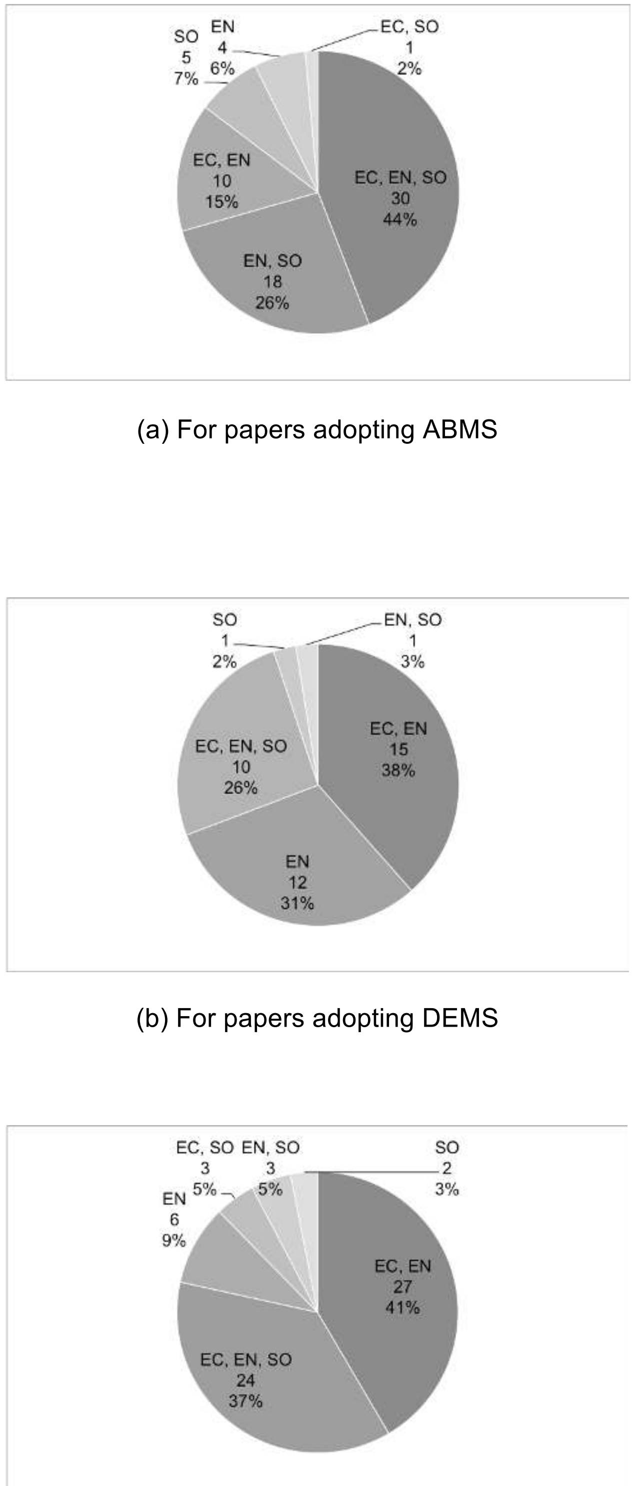

(a) Bar Chart




(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

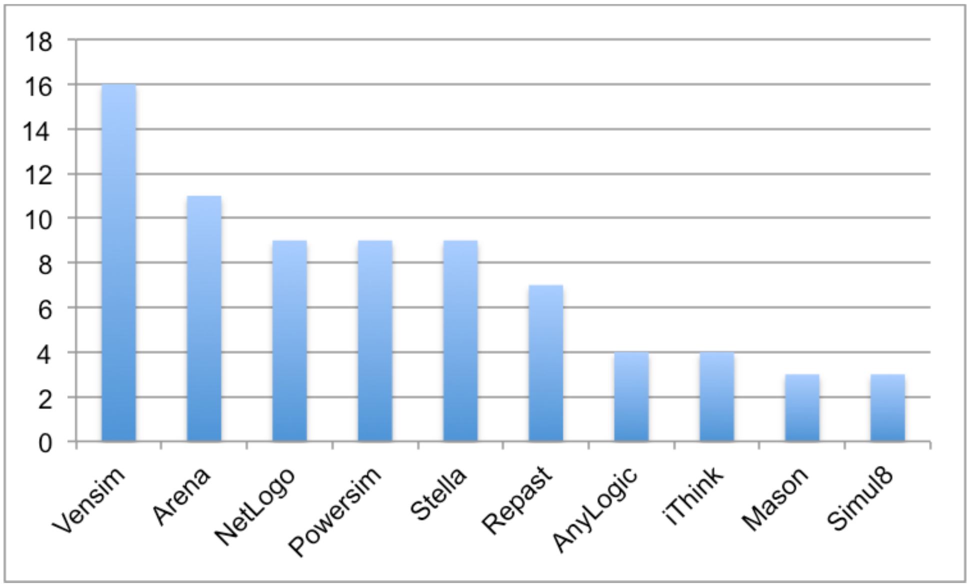


(b) For papers adopting DEMS

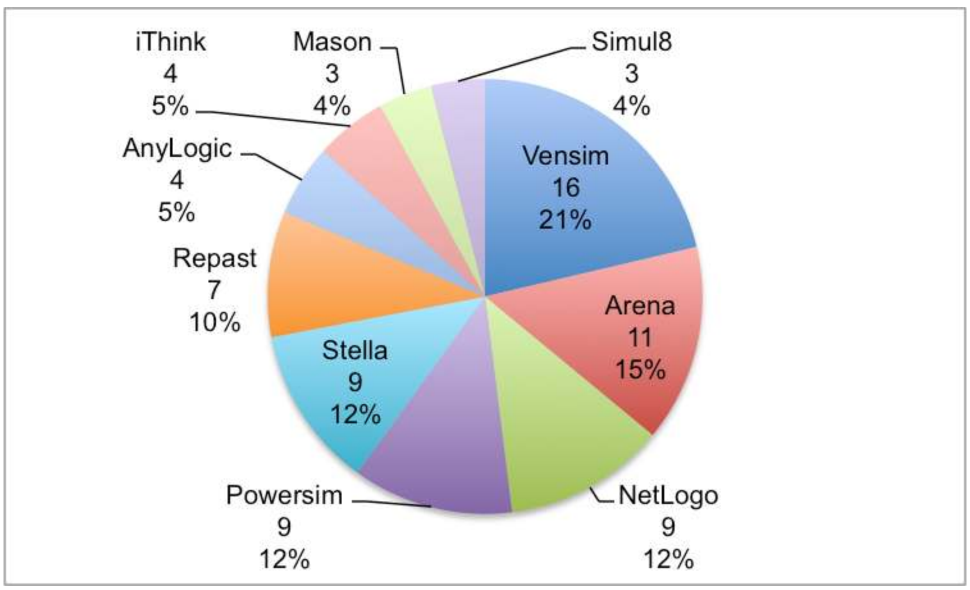


(c) For papers adopting SDMS

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

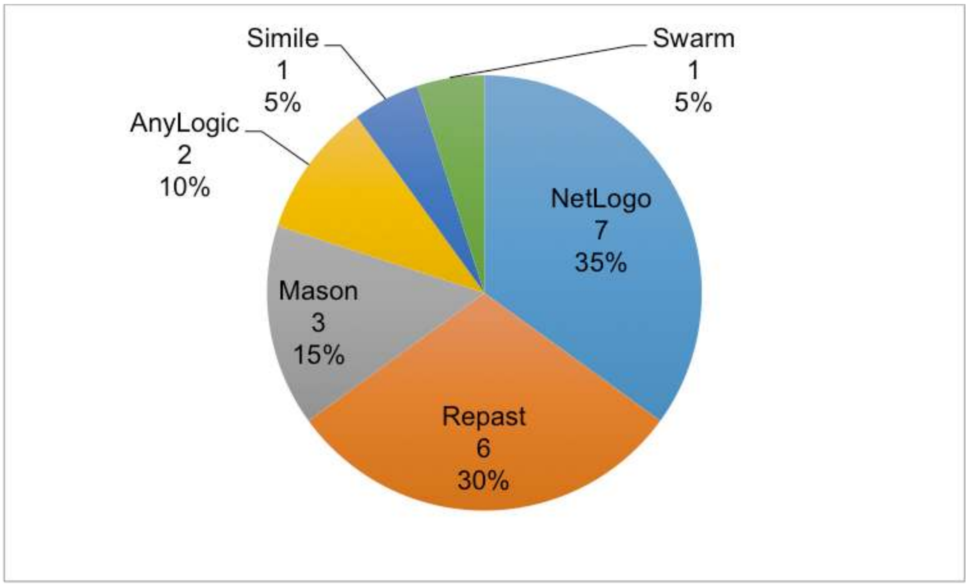



Figure 8. Uses of Software Packages for Papers Adopting ABMS

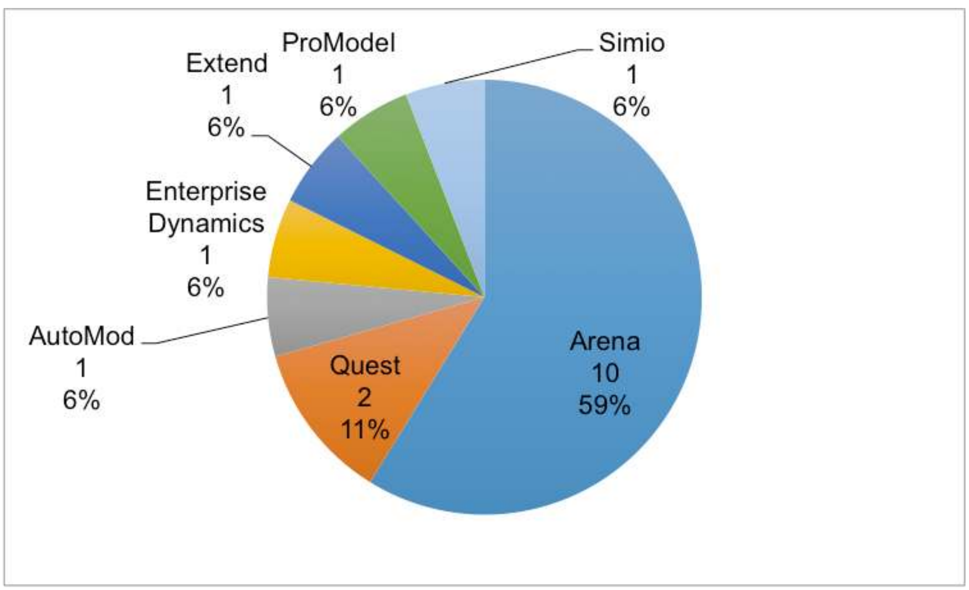



Figure 9. Uses of Software Packages for Papers Adopting DEMS

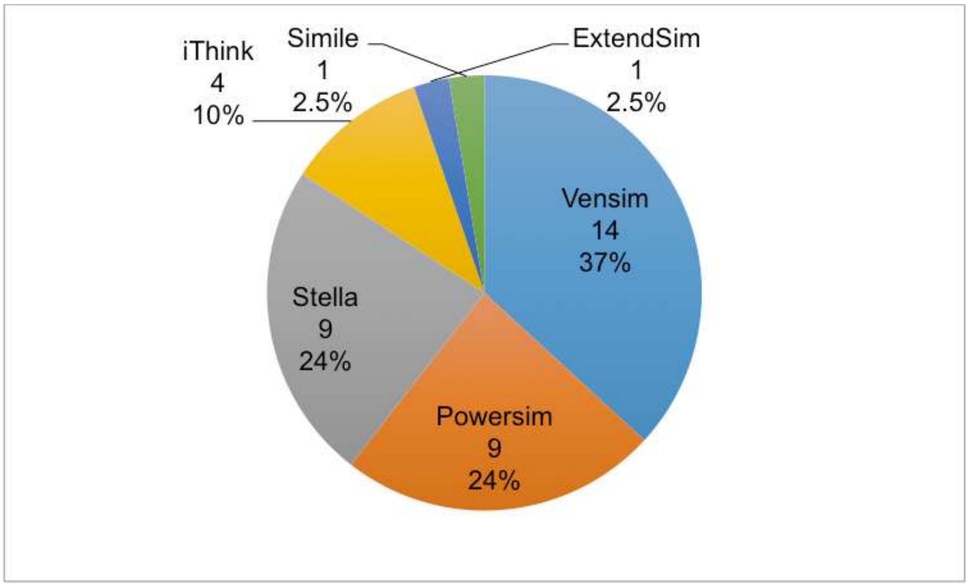



Figure 10. Uses of Software Packages for Papers Adopting SDMS