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A Systematic Review of Agent-Based Modelling and Simulation Applications in the Higher Education Domain

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A Systematic Review of Agent-Based Modelling and Simulation Applications in the Higher Education Domain

This paper presents the results of a systematic review of agent-based modelling and simulation applications in the higher education (HE) domain. Agent-based modelling is a 'bottom-up' modelling paradigm in which system level behaviour (macro) is modelled through the behaviour of individual local-level agent interactions (micro). This approach to considering the behaviour of systems of interacting 'agents' has been applied to a wide variety of domains. Of particular interest are the ways that ABMS applications have been used to further understand the dynamics of the HE domain. We conduct a systematic review of literature to analyse publications by year, role of the simulator, development stage of the models, and any associated validation. We also identify areas for future work, which includes an emphasis on validating existing and future models, detailed description of simulations to allow replication and further development, and the use of agent-based models in other contexts within the increasingly complex HE domain.

Keywords: academic activities; agent-based model; application and enrolment; higher education; simulation; student performance; systematic review; teaching & learning; university collaboration

1 Introduction

“We live in an increasingly complex world” (Macal & North, 2009, p. 2), comprising numerous individual and interrelated parts that form complex systems. The behaviours of individuals within the population impact on others, and these interactions give rise to higher-level emergent features. The common analogy is to that of a flock of birds. A high-level organiser does not control the flocking behaviour of birds. Rather, each individual bird follows a simple set of rules that relate to the position of neighbouring birds. From these simple rules, complex flocking behaviour arises. A key principle underlying complex systems thinking is that understanding emergent behaviour is best achieved through a ‘bottom-up’ process (Bonabeau, 2002) that seeks to discover the simple rules that govern the behaviour of the system as a whole. This approach to understanding systems and behaviours has been successfully used to study social systems, particularly those exhibiting the characteristics of competition and collaboration (Axelrod, 1997). These characteristics are true for higher education, as knowledge dynamics in universities are difficult to study with conventional quantitative analysis (Triulzi, Scholz, & Pyka, 2011).

Agent-based modelling and simulation (ABMS) is a computational approach to modelling systems comprised of interacting, autonomous, decision-making ‘agents’ or individuals (Bonabeau, 2002; Macal & North, 2009). Typically, agent-based models contain three elements: *agents*, their *relationships* and methods of interaction, and their *environment* (Macal & North, 2010). In ABMS, agents repeatedly interact, influencing each other, learning from their experiences, and adapting their behaviours so they are better suited to their environment. Within an ABMS, agents can be representations of any type of self-governing individual or entity (Crooks & Heppenstall, 2012) with behaviours described using simple rules. Agents interact with other agents, which in turn influences their behaviours and the system of which they are comprised (Macal & North, 2009, 2010). Reasoning the individual agent’s decision and interactions with others in their environment (Crooks, 2012) leads to emergent macro-scale phenomena (Bonabeau, 2002).

ABMS can also be considered as a virtual laboratory for theory improvement (Grimm et al., 2005; Macy & Willer, 2002; Triulzi & Pyka, 2011). The ABMS development process consists of three stages: construction of a conceptual model based on relevant literature, development of a computational model of the dynamic processes, and validation. Running the computational model is called ‘simulation’, during which the dynamic processes of agent interaction are simulated repeatedly over time (Macal & North, 2009) to explore for emergent phenomena. Simulation experiments using a validated computational model suggest theory for how the dynamics of systems emerge from bottom-up processes (Grimm et al., 2005), and ultimately contributes to advance understanding of the system (Triulzi & Pyka, 2011). As an example, Henrickson (2002) developed a students’ college choice and college access conceptual model based on a literature review. They implemented the agent-based model and validated the model using a national data set on incoming freshmen from 1994. This flow predictor model consisted of ‘student agents’, ‘university agents’, the actions of each agent type, and the interactions between students and universities. This agent-based model was used to analyse the college choice / college access problem in higher education and was successfully used to predict enrolment at colleges.

ABMS has a number of benefits compared with other modelling techniques. Firstly, it has the ability to capture emergent phenomena (Bonabeau, 2002; Malleson, 2012;

Matthews, Gilbert, Roach, Polhill, & Gotts, 2007); that is, behaviours not explicitly specified in micro-level decision or behavioural rules that emerge at the macro-level. Secondly, ABMS provides an environment for the study of naturally occurring systems (Bonabeau, 2002). For example, modelling how individuals move around a city is a more natural approach to modelling crowd behaviour than using simultaneous equations to represent crowd behaviour. Thirdly, ABMS is flexible (Bonabeau, 2002), as the number of agents, and their behaviours can be easily changed (Bonabeau, 2002), which is a key aspect in conducting simulation experiments. Fourthly, ABMS are well suited for integration with geospatial systems (Crooks & Heppenstall, 2012), such as geographic information systems (GIS) (Crooks, 2012) as this allows for the exploration of complex systems in a way that preserves space and time.

The increasing interest in ABMS has led to a number of reviews. For example, Matthews et al. (2007) reviewed the use of agent-based modelling to further understanding of human decision-making in land use. Similarly, (Bousquet & Le Page, 2004) reviewed the role of agent-based simulation for ecosystem management, and specifically to study the interactions between ecological and social dynamics.

In recent times, new dynamics in higher education (HE), driven by changes in demand, diversification, changing lifelong learning needs, social engagement and technology (Meek, Teichler, & Kearney, 2009), provide a fruitful space for ABMS applications. It is therefore timely to review the existing state and development of ABMS applications in the HE domain. We aim to identify ABMS use within HE, including the level of the model development, and thus possible directions for future work. Specifically, our work aims to answer the following research questions:

- RQ. 1: What specific dynamics do existing ABMS applications cover in HE?
- RQ. 2: What is the current level of development of ABMS applications in HE?
- RQ. 3: What are the opportunities for future work?

We adopt a systematic approach to the review of literature on ABMS. A systematic review is developed to gather, evaluate, and analyse all the available literature relevant to a particular research question, or area of interest, based on a well-defined process (Bearman et al., 2012; González, Rubio, González, & Velthuis, 2010; Kitchenham & Charters, 2007). The systematic review methodology is extensively used in the healthcare domain (Bearman et al., 2012), and has been widely adopted in different domains, including business (González et al., 2010), education (Bearman et al., 2012), and software engineering (Šmite, Wohlin, Gorschek, & Feldt, 2010).

The value of a systematic review is in providing a transparent, comprehensive and structured approach to gathering, evaluating and analysing the literature (Bearman et al., 2012), resulting in a repeatable process. A specific and well-defined approach is the key to systematic review, which ensures that the most relevant studies with regard to a specific research question are obtained (González et al., 2010). It makes it less likely that the results of the literature are biased (González et al., 2010; Kitchenham & Charters, 2007). However when compared with the narrative review methodology, which focuses on critique and summarisation of ‘relevant’ studies and knowledge in a subject area (Baumeister & Leary, 1997), the systematic review approach is considered to require more effort on the part of the researcher (Kitchenham & Charters, 2007).

In the following sections, we present our review of ABMS applications in HE. In Section 2, we detail our systematic methodological approach. The results of the review, and corresponding answers to the research questions, are provided in Section 3. We summarise our findings and provide a discussion of possible strategies to enhance ABMS applications in the HE domain in Section 4.

2 Methodology

A systematic review methodology requires the identification of all published works relevant to the requirements. The search strategy adopted covers key term searches in relevant scholarly databases and search, as determined through librarian consultation. Some database searches failed to return any relevant results and are excluded from the results. The key sources and parameters of the search are listed in Table 1.

Table 1. Search sources and parameters

Bibliography Databases: (With studies found)	Web of Knowledge, ACM Digital Library, Proquest, ScienceDirect Journals, SCOPUS, SpringLink, EBSCO MegaFile Premier, Wiley Online Library, Computers and Applied Sciences Complete, Engineering Village, Oxford Journals Online, Sages.
Search Engines:	Google Scholar, and Google.
Article Type:	Journal articles, conference papers, working paper, book sections
Search On:	Title, Keywords, Abstract, Full Text
Sorting on Returns:	Sort by Relevance
Language:	English
Publication period:	Unlimited

To conduct a review that meets our objectives, the search query needs to accommodate two key purposes. The first purpose is to find published works relating to ABMS applications. The relevant search keywords are listed in the Component 1 section in Table 2. The second purpose is to find applications used in the HE domain. In this review, HE represents education targeting undergraduates and postgraduates, and teaching and research work carried out by academic researchers and professors at tertiary institutes, colleges, and universities. We exclude ABMS applications for general education, early education, primary education, and secondary education. The search keywords to locate these works are listed in Component 2 section in Table 2.

Table 2. Search keywords

Component 1: inclusion (Compulsory)	‘agent-based model’, ‘agent-based simulation’
Component 2: inclusion (Compulsory)	‘higher education’, ‘university’, ‘college’, ‘academic’, ‘professor’, ‘undergraduate’, ‘postgraduate’, ‘researcher’
Component 3: exclusion (Optional)	-‘geography’, -‘land use’, -‘finance’, -‘economics’, -‘medical’, -‘physics’, -‘chemistry’, -‘traffic’, -‘biology’, -‘ecology’, -‘archaeology’, -‘immune’, -‘supply chain’, -‘military’, -‘animal’, -‘aerospace’, -‘health care’, -

	‘immunology’, -‘transportation’, -‘psychology’, -‘e-commerce’, -‘telecommunication’, -‘nature resource’, -‘consumer’, -‘criminology’, -‘demography’, -‘philosophy’, -‘physics’, -‘auctions’, -‘mechanical engineering’

From these individual keywords, the following Boolean search string, covering Components 1 and 2, was applied to all the information sources:

> (‘agent based simulation’ OR ‘agent based model’) AND (‘higher education’ OR university OR college OR academic OR professor OR undergraduate OR postgraduate OR researcher)

Where a search returned thousands of results, exclusion terms were manually identified and applied to the search results (Component 3 section in Table 2) to locate potentially irrelevant articles only. That is, articles are systematically evaluated for relevance by considering the title, abstract and, if necessary, content, of an individual article. An article is considered relevant if it a) applies or considers an agent-based approach, and b) the focus of the ABMS is a facet of the HE system. The exclusion terms were selected due to their high incidence of co-occurrence in search results with Components 1 and 2 on a case by case basis.

From the twelve bibliographic databases and two search engines, we identified a total of 36,612 articles using our search strategy based on Component 1 and 2 (Table 3). The keyword ‘university’ results in more articles being discovered than expected, as this term frequently appears in article details. Essentially, a large amount of research using ABMS appears within the research topics identified by the exclusion terms, and is returned by the search string due to the author(s) relationship with a HE institution. In these instances, the HE domain is not the subject of the ABMS and therefore the results are not relevant to this study. Thus significant manual screening of titles, keywords, and abstracts of literature was required, involving iterative searches that first identified, then used, the exclusion terms. In cases where insufficient information was available in these fields to determine relevance of an individual article, the full text of the potential literature was peer reviewed. Any conflicts were resolved by consensus between the authors. Due to the large amount of non-relevant search results, this systematic review required a significant manual effort to locate the final set of relevant articles.

Table 3. Summary of search results

Database	Discovered	Relevant
Web of Knowledge	157	6
ACM Digital Library	3795	6
Proquest	3574	5
ScienceDirect Journals	3429	3
SCOPUS	123	11
SpringerLink	5404	3
EBSCO MegaFile Premier	3798	12
Wiley Online Library	1924	3
Computers and Applied Sciences Complete	363	4
Engineering Village	3474	10

Oxford Journals Online	104	1
Sages	408	1
Google Scholar	9570	17
Google	489	8
SUMMARY	36612	90

From the identified articles, 90 were determined to relate specifically to ABMS in the HE domain based on the full content of the article. After accounting for duplicate returns, 42 unique relevant articles were located. Of these, seven were found to be of 'limited-relevance'. These articles focus on the social behaviour of individuals, where the university or higher education context is not explicitly relevant, and were thus excluded. For example, in models of student drinking behaviour, the higher education context is not considered to be the primary focus of the work, rather it is considered contextual only to the phenomena of interest. As a result, a final set of 35 relevant articles was identified.

3 Results

The results of the systematic review are structured based on the research questions stated in Section 2. These results are based on the 35 relevant articles finalised through the process of searching, screening, mapping, data extraction, and quality assessment.

3.1 What specific dynamics do existing ABMS applications cover in HE?

To answer this research question, we classify the models based on the agents of each model, relationship between the agents, users of the model, and the purpose of the model. We have identified six broad categories: (a) university system (b) university collaboration (c) academic activities (d) application and enrollment (e) student performance, and (f) teaching and learning.

University system. Only one of the 35 articles located was used to study a university as an independent 'organisational' system. Roebber and Meadows (2012) employed an agent-based model to examine strategic approaches at 13 American campuses. The simulation results suggest that incentivising productivity improvements is the best option for universities to maintain system affordability and quality in the face of long-term funding constraints. This model is not validated either conceptually or operationally, and can therefore be regarded as an entry point for ABMS researchers to investigate university systems further.

University collaboration. Four articles were located where university collaboration was the focus, with three of these developed to explore the relationship between universities and industries. These models, developed by Ahrweiler, Pyka, and Gilbert (2011), Triulzi and Pyka (2011), and Triulzi et al. (2011), adopted the 'kene' concept (Gilbert, 1997) to model knowledge transfer among universities and firms. In the computational implementation, 'kene' is a sequence of bits to represent a quantum of knowledge (Gilbert, 1997). The simulation results of these models have similarities, with collaboration found to raise the knowledge and competence level of both universities and high-tech firms, increase innovation diffusion in terms of quantity and speed, improve the attractiveness of firms to other industries when new partnerships are considered, provide financial benefits, and tending to shift universities from a basic to an applied research orientation.

Cooperation within the HE sector was the focus of a study using ABMS by Zhang, Zhao, and Zhu (2009). Focussing on financial indexes, income and expenditure rather than knowledge transfer, this model was built to analyse the growth of the HE sector under different cooperative strategy dynamics. Simulation results show that the size of regions has a negative impact on growth rate, and initial simulation conditions can impact on collaborative efforts.

Academic activities. ABMS has been widely used to explore academic activities, with 12 of the 35 studies assigned to this category. These studies involve talent recruitment (Caillou & Sebag, 2009), talent management (Phelan, 2004; Stepanić, Pejić Bach, & Kasać, 2013; Zheng & Lei, 2010), academic collaboration (Fujii & Tanimoto, 2003; Kenna & Berche, 2012), publication (Gilbert, 1997; Mölders, Fink, & Weyer, 2011), peer review (Cabotà, Grimaldo, & Squazzoni, 2013; Paolucci & Grimaldo, 2012; Squazzoni & Gandelli, 2012), and academic-level research funding (Hoser, 2013).

Caillou and Sebag (2009) implemented an ABMS application to investigate how universities can recruit the best employee candidates with high confidence. The simulations indicate that ‘top’ and ‘medium’ rated universities have no difficulty in recruiting the talent they have selected, while ‘bad’ universities are likely to struggle to secure the recruitment of acceptable candidates. In contrast, Zheng and Lei (2010) used ABMS to study talent management to resolve issues relating to knowledge innovation and academic impact in universities, demonstrating that a knowledge innovation-oriented stance in managing talent leads to better systematic efficiency.

An ABMS application with a focus on exploring career paths for young researchers in HE was implemented by Stepanić et al. (2013). In their model, young researchers can choose to be a teacher in universities, transfer to industry, or work in non-scientific education institutions such as schools or colleges. Unfortunately the model is partially implemented, thus future work is required to generate verifiable results.

To reach a better understanding of the choice of promotion systems in various institutional contexts, Phelan (2004) adopted an ABMS to simulate promotion systems in the HE domain. The simulation results show that a partial ‘up-or-out’ system was successful. This particular promotion system appears to exploit the learning/hiring trade-off by promoting good performers, bringing in superior performers when necessary, and facilitating learning at senior levels.

Fujii and Tanimoto (2003) studied the influence of professor leadership on research group performance in Japanese universities using an ABMS approach. The simulation results show that the team performs more efficiently if the professor doesn’t have definite leadership over the research team. Similarly, Kenna and Berche (2012) implemented an ABMS application to gain insight into the optimal size of research groups for quality research performance. The simulation indicates a linear relationship between group research quality and group size, to an upper critical limit beyond which research quality no longer increases significantly with group size.

Gilbert (1997) implemented a simulation of academic paper generation. Through the model, academic activities, including the publication of academic papers, citation behaviour, research collaboration, and their relationships, are observed. The simulation successfully produces a specialty structure with an ‘area’ of science displaying realistic growth and decline. The model also reproduces Lotka’s Law regarding the citation distribution among authors.

Similarly, Mölders et al. (2011) proposed conceptual model investigates how the scientific publication system works. In the proposed agent-based model, individual academics rationally decide where to publish their papers. However, the model requires calibration, implementation, and validation to evaluate its utility.

Squazzoni and Gandelli (2012) applied ABMS to investigate whether the quality and efficiency of peer review is influenced more by scientists' behaviour, or by the type of scientific community structure (homogeneous versus heterogeneous). The simulation results show reciprocity can have a positive effect on peer review only when referees are not self-interest driven, and strictly follow standards of fairness. To better understand the importance of fairness in peer review processes, Paolucci and Grimaldo (2012) and Cabotà et al. (2013) also investigated the influence of honesty in the process. The simulation results of both studies show that a small proportion of dishonesty in the review process may dramatically distort publication quality.

Research requires funding, particularly when there is an emergence of new technology or academic specialty. Hoser (2013) developed an ABMS application to analyse how public third-party funding influences the diffusion of high technology. The ABMS application was implemented to analyse the funding and innovation systems in the US and Germany. The simulation results show that different ways of funding researchers can influence the pattern of diffusion of a new technology in academia. This is particularly true in larger research systems (i.e. the US).

Application and enrolment. How universities select students, how students choose which university to attend, and how students choose majors, are key interactions among universities and students that have attracted attention from ABMS researchers.

Henrickson (2002) built a validated computational model based on McDonough's (1997) research using Bourdieu's (1984) sociological theoretical framework (as cited in Henrickson, 2002, p. 4). The model follows simple rules; individual students make decisions about which college to attend, and educational institutions make decisions about enrolling a student. The macro-scale phenomena of overall enrolment patterns observed in universities are considered.

Moskovkin (2009) extended this model at the conceptual level, allowing for students to make applications and decisions over the universities ranked within the top 500 in the world. Influential factors used to evaluate universities are considered, and thus student-university choice is modelled based on individual preferences.

Reardon, Kasman, Klasik, and Baker (2013) implemented an ABMS application that focussed on how family resources influence university application choices, and patterns of stratification in university enrollment. The model shows how the relationship between student resources and student performance drives most of the observed socioeconomic sorting of students into universities. It provides evidence that increasing income-achievement gaps may have strong and lasting effects on students' life outcomes, which in turn could have negative impact on intergenerational mobility.

The 'agent' mindset was also applied to simulate students' choice of Science, Technology, Engineering, and Mathematics (STEM) majors. Motivated by a decrease in enrolments in STEM, Allen and Davis (2010) carried out their study using ABMS. The model indicates that changes with minimal (if any) financial cost could more than double the STEM yield.

Student performance. Of the 35 articles, only four articles are related to student performance. These articles relate to simulation of online peer support (de Bakker, van

Bruggen, Jochems, & Sloep, 2011), students' grades (Wejnert, 2006), and graduate employment (Cai, 2013; Mori & Kurahashi, 2011).

In their study of a peer support online system for students, de Bakker et al. (2011) applied ABMS to assess the dynamics prior to the system design and implementation. The study was focussed on peer competence and sustainability of the proposed peer support online system.

In response to macro-level grade inflation, Wejnert (2006) developed an ABMS application to investigate grades, and the drivers interacting with grades. The simulation results show that three micro-level processes lead to significant increases in overall grades, and significant reductions in the effort required achieving those grades.

Mori and Kurahashi (2011) developed an ABMS application to improve the effectiveness of job matching processes for new graduates. The simulation indicates Profit Sharing and Actor-Critic methods, two types of reinforcement learning contained in the model, effectively support students' job-hunting activities and raise the finding-employment proportion of the entire graduate employment market.

Considering the process from the employers perspective, Cai (2013) provided a conceptual framework to understand employers perceptions of graduates with similar educational credentials in the workplace. In this framework, graduates' employability is influenced by a number of factors and mechanisms, including exogenous factors, initial signalling effects and the processes of both private and public learning.

Teaching & learning. It could be argued that the actual teaching of ABMS techniques, or using ABMS as a teaching aide, is not as relevant to our study as those studies using ABMS to analyse dynamics of the HE domain. However, its popularity in learning contexts warrants its inclusion. For example, ABMS has been to teach university-level students in areas such as ABMS itself (Kurkovsky, 2013; Pinder, 2013; Shiflet, Shiflet, & Sanders Jr, 2013), material science (Blikstein & Wilensky, 2006a, 2006b, 2008), geography (Brewington, Engie, Walsh, & Mena, 2013), chemistry (Stieff & Wilensky, 2003), civil engineering (Zhu, Xie, & Levinson, 2010), and biology (Kottonau, 2011). Therefore it is worth mentioning that ABMS, both as a teaching facilitator and as an educational tool, has been widely accepted in university-level teaching contexts.

3.2 What is the current level of development of ABMS applications in HE?

Meta-analysis is conducted to study the level of development of ABMS applications in the HE domain. The comparisons are based on indicators from the data extraction scheme and include the number of articles by publication year, category, development stage and role of the simulator.

The distribution of the number of articles per year is shown in Figure 1. This clearly shows that the ABMS approach has become more popular in the HE domain since 2009.

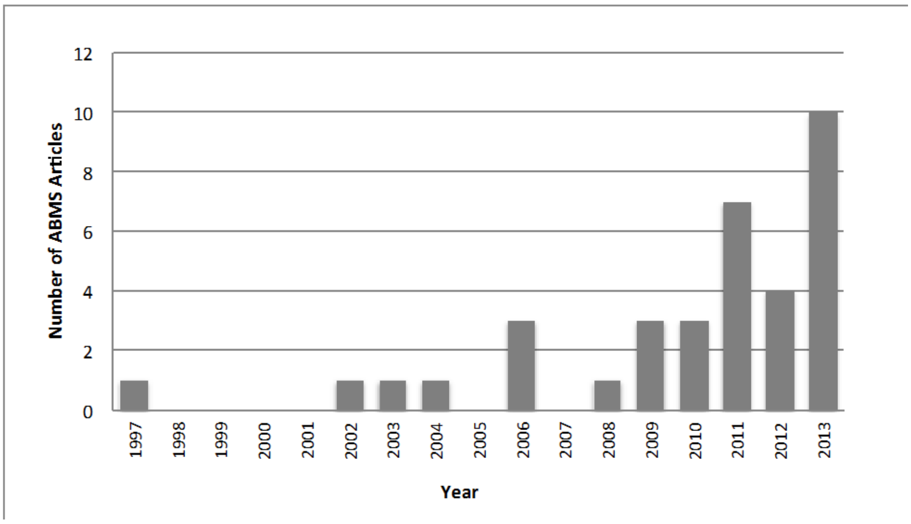

Figure 1. Number of articles by publication year.

Based on the category specification outlined in Section 3.1, the distribution of the number of articles per category is shown in Figure 2. The complex dynamics occurring in academic activities has received considerable interest from ABMS researchers. The use of ABMS for teaching and learning purposes is also an area attracting attention.

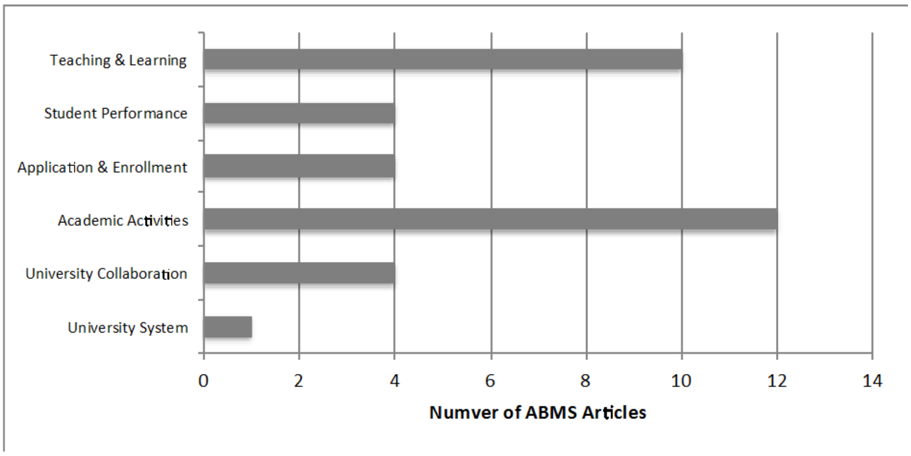

Figure 2. Number of articles by category.

Based on the level of understanding of the real world system, Heath, Hill, and Ciarallo (2009) define the role of agent-based models as being on a continuum between generator and predictor, with the mid-position considered as a mediator role.

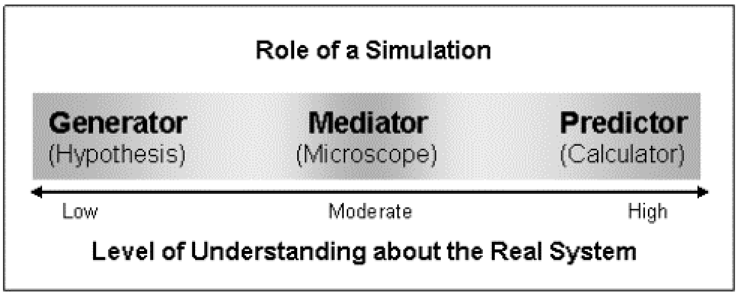

Figure 3. Role of a simulator (Heath et al., 2009).

As shown in Figure 3, a simulation model can act as a generator of hypotheses and theory about the macro-scale phenomena of real systems when the system is not well understood. When the system is thoroughly understood, the model acts as a predictor of the real world system. If the theory can be improved and subsequently the model can be improved, the model can be considered to act as a mediator between theory generation and prediction.

The role of the ABMS applications identified in our review was assessed according to the aims of the simulation stated by the author(s). Figure 4 shows that ABMS researchers have a greater level of understanding of the real systems under study in the areas of university collaboration, academic activities, and application and enrolment.

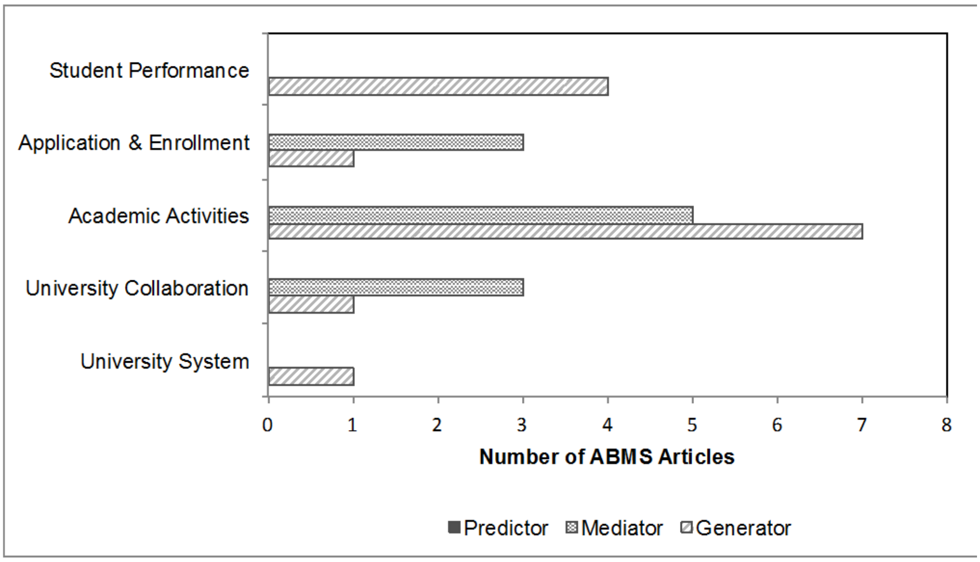

Figure 4. Number of articles by simulator role group by category.

In our review, we specify three stages of ABMS application development to describe how complete or functional the model is. The first stage is a conceptual model, whereby an agent framework for the subsequent development of an ABMS is presented. In the second stage, a computational model is presented. In this instance the conceptual model has been implemented in a software environment and thus an ABMS implementation is presented. The third stage is considered a validated model; the authors present a computation model, and the results of the model have been tested against the real world phenomena in some way. ABMS applications for teaching and learning purposes are not implemented for analysing complex dynamics in HE and are thus not considered generative. Out of 25 remaining ABMS applications, there are 10 validated models (40%). The development stage of all the articles is shown in Figure 5.

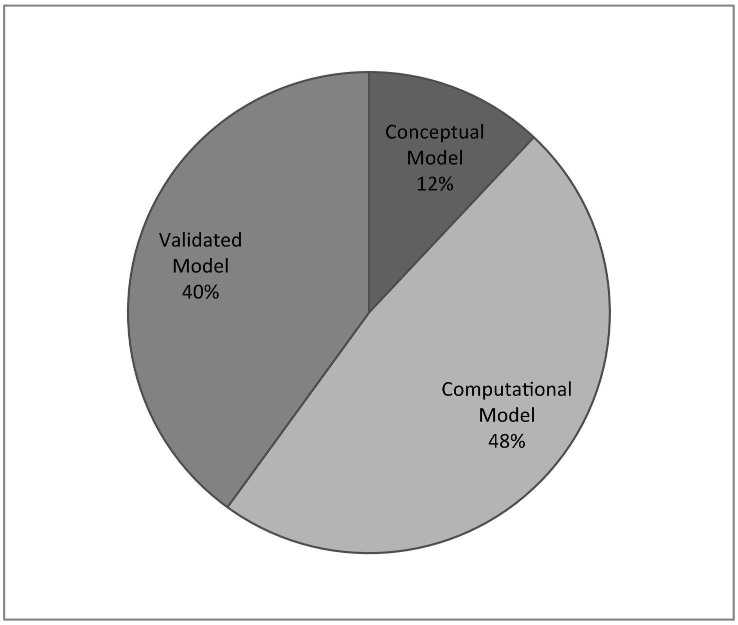

Figure 5. Articles by development stage.

3.3 What are the opportunities for future work?

The availability of quality data to validate ABMS applications is an issue (Cabotà et al., 2013; Paolucci & Grimaldo, 2012). Among the 35 studied articles, only 10 models are operationally validated. Fundamentally, models that are both statistically and non-statistically validated can be robustly defended as representative of real world phenomena, and thus can best advance knowledge of the system being modelled (Heath et al., 2009). In terms of data for validation purposes, a number of global university ranking systems have been released since 2003 (Dill & Soo, 2005) provide multiple, comparable measures of HE institutions, including performance, academic output, and student populations. One possibility for future work is to make use of this data, or collect other relevant quality data, for validation purposes.

During our review, we also observed that few ABMS computational models were open source. That is, the code used to build the model, or sufficient detail to implement a replica, was not available. Making models open source will enable other researchers to replicate the models. Potentially, when additional data becomes available and/or further research interest occurs, existing ABMS applications can be reviewed and possibly advanced.

Over the past two decades, the HE area has become increasing complex. Factors such as reduced public funding, collaboration with industries, internationalisation and commercialisation (Wright, Lockett, Clarysse, & Binks, 2006) have had significant impacts on the sector. Universities have dramatically expanded international activities, with a particular example being a growth in offshore campuses (Altbach & Knight, 2007). Similarly, commercialisation has become a more popular university activity (Wright et al., 2006), with Lambert (2003) noting an increase in the number of university spin-off companies established (as cited inWright et al., 2006, p. 1). As the results of our review demonstrate, ABMS is a technique applicable to a wide range of dynamics in the HE domain. With the dramatic changes occurring in the HE landscape, future work that broadens the use of ABMS in HE domain, to assist researchers, and ultimately managers and decision makers, to understand the complex scenarios occurring, and also to model alternative scenarios to capitalise on opportunities, is a valuable area for future work.

4 Conclusion

Social phenomena in the HE domain are unpredictable and dynamically changing, and ABMS is one of the available techniques that can be used to observe and understand these complex systems. ABMS has been increasingly used in the HE domain in the last five years. From existing literature, ABMS has been used to model the university system, university collaboration, academic activities, application and enrollment, and student performance. In addition to being used as a tool to model complex interactions for 'what-if' scenario analysis in the HE area, it is also used in a learning context for students. In this way it has been employed to teach either ABMS itself, or to help students understand complex dynamics in areas such as material science, engineering, geography, chemistry, and biology.

Among the six specific research directions we identified, the study of academic activities has attracted the most research interest. University collaboration, academic activities, and student application and enrolment have been explored using ABMS applications, and these areas generally exhibit the most validated models. Regardless of their purpose, all the 35 ABMS applications identified provide insights into the dynamics and interactions in the areas under study.

While the usefulness of an ABMS approach has been well documented, the development and application of these models is not without limitations. The success of an ABMS in any given area must be gauged by how accurately they reflect the behaviour of the real world system under study (Edmonds, 2001). From the results of our review, 60% of the ABMS articles discovered failed to validate the model in some way against the target system. Thus, while we identify studies utilising ABMS in HE, uncertainty exists over how well these models reflect the system dynamics they are concerned with.

Similarly, few articles provided detailed pseudo or source code for the computational models. With ABMS, there is the potential for artefacts or errors to be introduced during the often-complex conversion from a conceptual to a computational model (Galán et al., 2009). The availability of source code is key to detecting errors and artefacts, which can significantly decrease the validity of an ABMS.

The limitations of our approach must also be considered. While the selection of inclusion terms for this study was uncomplicated, the identification of appropriate exclusion terms was iterative and complex, leading to significant manual processing of search results. There is potential that relevant articles have been excluded due to the scale of the task. Also, although expert advice was sought on the appropriate scholarly databases to include in the search parameters, research outputs not indexed in these major databases may have been missed. The inclusion of popular search engines is an attempt to address this potential limitation.

Despite these limitations, this study also identifies opportunities for future work. The quantity and quality of data available to validate ABMS applications is a well-known, open issue. Since 2003, multiple global university ranking systems have been released, providing indicators of the performance of universities, their academics, and their students. One potential area for future work is to utilise these data for the purpose of validation of ABMS in the HE area. Another direction is to encourage more open source publishing of ABMS models, with documentation containing sufficient detail for future replication and potential further development.

The HE sector is complex in nature; individuals collaborate and compete at all levels of the system. External forces are changing the HE landscape and it is important to understand how the system is currently operating, as well as how it is likely to be impacted in the future. ABMS has proven potential to assist us to better understand these complex phenomena.

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