Teaching Agent-based Modeling for Simulating Social Systems – A Research-based Learning Approach

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Abstract. Existing courses on agent-based modeling and simulating (ABMS) are mainly aimed at doctoral students and many modelers have acquired their ABMS skills by teaching themselves. This paper reports and reflects on the development of an undergraduate course on ABMS of social systems. It presents a problem-based approach to teaching ABMS of social systems, Integrated Learning Outcomes (ILOs), and the pursued course outline. This paper discusses the constructive alignment of the syllabus, presents the results from the course evaluation, and draws conclusions for further editions of the course. Rather than proposing how such courses should be structured, we discuss the feasibility of the pursued research-based learning approach. Our goal is to inspire other researchers and teachers to develop similar courses, to encourage the establishment of a general curriculum, and to promote ABMS in undergraduate education.

Keywords: Agent-based Social Simulation, Teaching, Education, Problem-based Learning, Inquiry-based Learning.

1 Introduction

Agent-based Modeling and Simulation (ABMS) of human behavior and social phenomena is increasingly applied across different disciplines. Lately, its potential to facilitate policy modeling and decision support has gained attention. During the Covid-19 crisis, ABMS have been used to simulate the consequences and effects of different non-pharmaceutical interventions on society [1]. Also in other areas, e.g., land-use, fishery, agriculture, and transportation, increasing collaborations between agent-based modelers and policy actors and an interest in ABMS of social systems can be observed [2].

In academia, agent-based modelers have diverse backgrounds, and many have acquired their ABMS skills by teaching themselves. This might be due to a lack of standard teaching materials, training programs, and integration into higher education programs and curricula [3]. Some ABMS courses exist, e.g., summer schools and short tutorials, but these are mainly aimed at doctoral students. The participants of these courses often have diverse (non-technical) backgrounds and attend the training to receive a first introduction to ABMS, which they need for their PhD projects [4]. Many are committed to using ABMS and actively search for suitable courses, either because they self-identified the need to take a course on this topic or because they were recommended to do so by their doctoral supervisors.

In undergrade education, the situation is different. ABMS is rarely part of the higher education curriculum and, if existing, stand-alone (elective) courses are offered. Also, undergraduate students do not usually have the intrinsic desire to learn about ABMS as many have neither heard of this method nor face issues that benefit from or suggest the use of ABMS. What makes teaching of ABMS challenging at undergraduate level is the method's inherent interdisciplinarity, required prior knowledge, skills, and understanding (e.g., in computer science, behavioral science, and statistics), and the diverse range of ABMS applications (e.g., in biology, ecology, and economics) [5].

To promote the advancement of ABMS, to establish ABMS as a well-trusted tool for knowledge generation and in decision support, and to train the next generation of agent-based modelers, we believe undergraduate education needs to be advanced. We developed an elective undergraduate course on *agent-based modeling for simulating social systems*. The goal of this course is for the students to develop both knowledge and skills on the use of ABMS as tool and research method for analyzing social systems and phenomena. We pursue an inquiry-based learning approach, which is a learning form that actively engages students in the learning process, encourages a high level of participation, and promotes the development of problem-solving strategies.

This paper reports and reflects on the development of this course and on the experiences from teaching its first edition. We present a problem-based approach to teaching ABMS of social systems, the Integrated Learning Outcomes (ILOs), and the course outline we pursued. We discuss the constructive alignment of the syllabus, present results from the course evaluation, and draw conclusions for coming editions.

The course was hosted at Malmö University, Sweden, and was given for the first time in Spring 2023 as an elective self-study course. The presented syllabus is by no means intended as a silver bullet to teaching ABMS. Yet, we believe that sharing of and reflecting on experiences from educating the next generation of modelers will inspire other teachers and facilitate the establishment of a curriculum.

The paper is structured as follows: Sec. 2 gives a brief introduction to research-based learning and an overview of practices in teaching ABMS. In Sec. 3., we present the ILOs and the outline of the course and Sec. 4 describes the constructive alignment. In Sec. 5, we present results from the course evaluation and draw conclusions in Sec. 6.

2 Background

2.1 Research-based Learning

Integrating research and teaching in higher education can enhance the students' learning experience and create a stimulating and productive learning environment [6]. It also facilities the shift from *teacher-centered education*, a traditional approach, where the teacher is in charge of learning and where students are passively being presented knowledge, towards *student-centered learning*, where the teacher functions as a facilitator (*teacher as partner*), embracing active learning [7].

In contrast to traditional teacher-centered education, which still is common practice in many technical disciplines, research-based approaches put the students in charge of their own learning by letting them independently carry out research as part of the course. This can promote a more symmetric teacher-student relationship and improve the students' learning experience. Moreover, practically experiencing the entire research process also facilitates the students' deeper understanding in contrast to, for instance, lying focus on memorizing facts as in traditional teacher-centered education [8].

Healey [9] argues that the active involvement achieved through research-based learning positively affects the students' depth of learning and understanding. However, they also emphasize that the development of research-based curricula is a demanding task for teachers as new approaches need to be developed that facilitate collaboration between students and teachers.

What is challenging when implementing a research-based teaching approach is to ensure *pedagogic resonance* between the learning design (i.e., the course design), the learning experience (i.e., learning activities), and the learning discipline (i.e., subject-specific traditions) [10]. Edwards et al. [6] emphasize that the integration of teaching and research does not happen on its own and that, depending on the practices and traditions of the discipline, one or the other part might be neglected. To achieve pedagogic resonance, it needs to be made clear for the students how this learning strategy relates to their studies and to cultivate expectations regarding roles and activities.

2.2 Teaching Agent-based Modeling and Simulation

In ABMS, which is often applied by researchers and in a scientific context, a strong connection between research and education seems inevitable. This connection is further endorsed by the fact that existing textbooks and courses are often tailored towards researchers and that there is a lack of standard teaching materials [11].

There are some scientific publications that discuss challenges in teaching ABMS and report on courses and pedagogical approaches. Macal & North [12] present different ABMS teaching strategies that they have successfully applied. They also propose different course outlines and suitable demonstration models. Lorig et al. [4] reflect on the learning outcomes and their experiences from a PhD tutorial on ABMS for policy making. During the Covid-19 pandemic, Bijak et al. [13] report on their experiences from teaching ABMS in an online setting and provide a blueprint for designing and running a course. There are also teaching reports from the earlier days of social simulations, e.g., Thorngate [14] and Carvalho [15], which present how specific simulation frameworks can be used. An example for teaching ABMS in a cross-disciplinary settings is presented by Augustijn et al. [16], who teach ABMS and machine learning.

3 Intended Learning Outcomes and Outline

The course consists of six Intended Learning Outcomes (ILOs), which define what students will be able to do upon successfully completing this course. According to the

Swedish Higher Education Ordinance[1] (Ch 6 Sec 4), the ILOs are defined based on six forms of knowledge: *knowledge & understanding*, *competence & abilities*, and *evaluation abilities & approach*. For formulating ILOs according to the different knowledge dimensions and levels of understanding, we used Blooms knowledge taxonomy [17], which provides examples of measurable active verbs (*action words*).

After completing this course, the student should be able to:
(knowledge & understanding)
ILO1) explain basic concepts in agent-based modeling and simulation
ILO2) describe how ABM can be used for simulation of social systems
(competence & abilities)
ILO3) implement agent-based models using simulation frameworks
ILO4) plan and perform simulation experiments
(evaluation abilities & approach)
ILO5) discuss the suitability of applying agent-based modeling and simulation
ILO6) evaluate and interpret simulation results

To support the students in achieving these ILOs, the course combines different working forms and learning strategies to ensure the constructive alignment. The course consists of three consecutive modules, which build on each other (see Fig. 1). Each module consists of a combination of carefully linked theoretical and practical learning elements, enabling the students to actively engage with practical exercises and examples, to promote learning though investigation, and the self-development of skills. To assess the students' learning progress, the course is examined through formative assessment (three written assignments) at the end of each module and summative assessment (a final project), which are mandatory and need to be successfully completed to pass the course.

The practical part (labs) is based on the NetLogo[2], which is an open-source and free-to-use multi-agent programing language and modeling environment. It is well suited for beginners but is also widely used by more advanced users in academic settings. We have chosen NetLogo for this course as it provides a variety of ready-to-use models, does not require previous programming skills, and allows for easily building visualizations and user interfaces to execute the model.

Even though ABMS course literature is sparse, there are some valuable textbooks to support student learning. We have chosen to combine chapters from different textbooks to provide optimal support. Two books that provide an intuitive and hand-on introduction to ABM are Railsback & Grimm [18] and Wilensky [19]. Both books use plenty example models in NetLogo to introduce core ABM concepts. To complement the simulation perspective, we used the books from Law [20] and Banks et al. [21], as well as Montgomery [22] to introduce experimentation. Finally, the social science perspective is provided by Gilbert & Troitzsch [23] and Robins [24]. In addition to these textbooks, different research articles are used in specific modules and submodules.

1 https://www.uhr.se/en/start/laws-and-regulations/Laws-and-regulations/ (accessed Mar 2024)
2 https://ccl.northwestern.edu/netlogo/index.shtml (accessed Mar 2024)

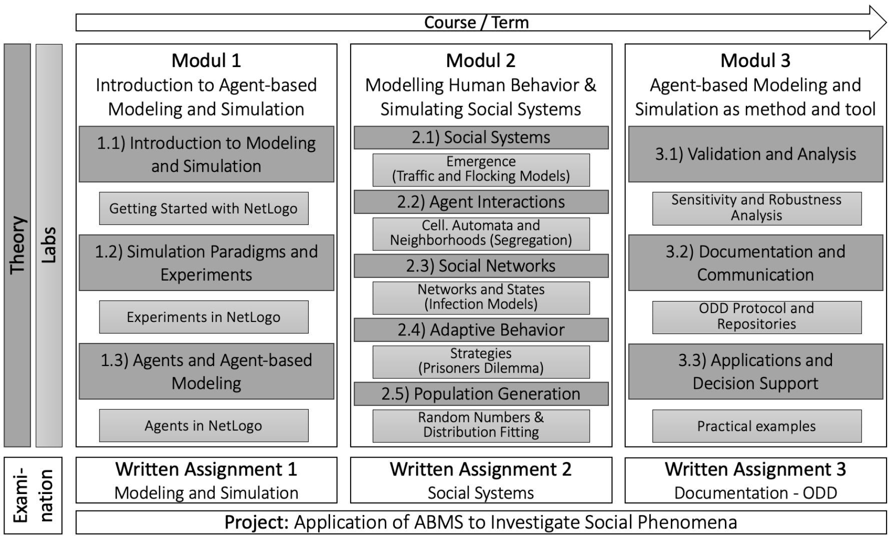

Fig. 1. Structure of the course: The course consists of three consecutive modules, each of which consists of theoretical (light grey) and practical (dark grey) learning elements. Each module is complemented by a written assignment (white), and a comprehensive final project (white).

3.1 Module 1: Introduction to Agent-based Modeling and Simulation

Module 1 introduces ABMS, assuming that the student does not have any prior knowledge on modelling and simulation. It pursues a problem-based constructivist approach, presenting and motivating interesting issues and questions that can be addressed using ABMS and promoting ILOs 1 and 4. After completing the module, the student is able to explain basic concepts in ABMS and to design simulation experiments.

Module 1 consists of three parts. The first part introduces simulations as a method to investigate and understand how complex systems work as well as the basic concepts of modelling focusing on abstraction and simplification. It motivates why modeling and simulation is well suited to investigate social phenomena and complex population dynamics using a real-world example of rabies, where individual-based models evidently lead to changes in the vaccination strategy [25]. This introduction is complemented by a hand-on NetLogo tutorial, where the students explore the user interface, run simulations, and modify model parametrizations using a wolf-sheep-predation model.

When teaching ABMS, it is debatable if modelling or simulation should be introduced first. To keep it novice friendly, and to not require programing skills, we have chosen to start with simulations. Hence, the second part focuses on simulations in general and introduces different simulation paradigms related to ABM, e.g., discrete-event simulation. It also introduces experimentation, presents different strategies, and gives a brief introduction to stochastic processes. The student will experience how simulations can be used to investigate and understand the behavior of a model, to then learn how to modify existing or develop own models. The second lab is on experimenting with the wolf-sheep-grass model, to systematically investigate the model's behavior.

Finally, the third part introduces different types of intelligent agents and the concept of ABMS to model complex behavior in artificial populations. A special focus is on what makes ABMS different from other modelling paradigms and when it is most beneficial to use ABMS. In the third lab, the student will also implement an own model. The exercises are designed as a code-along, where we encourage the students to try to solve the exercises on their own, yet, code examples are also provided that can be used.

The module is then concluded by a written assignment, where the different elements from the first module are combined, i.e., executing and understanding an existing model, developing a conceptual model, and implementing a model in NetLogo.

3.2 Module 2: Modeling Human Behavior & Simulating Social Systems

Module 2 focuses on achieving ILOs 2 and 3 and the student acquires an understanding of how ABMS can be used to simulate social systems and skills for modeling human behavior. Accordingly, this module focuses on situating the techniques taught in module 1 to applications in social systems. The first lecture introduces how different disciplines have contributed to and constituted the research area of ABMS, which also benefits the student orientation and how the ABMS could be situated in their field.

The introduction to modeling and simulation from module 1 allows us to introduce ABMS from a computational social science perspective. By introducing the weak notion of agency, opportunity structures, and institutional constraints of social systems, the goal is to enable the student to delineate and model social systems in society. To anchor these modelling concepts scientifically, the following lecture presents scientific theory about causality, methodological individualism, and experimental methodology. This is followed by concepts associated with simulation and the instantiation of models across time like interdependence, curve linear functions, and emergence. The submodule's lab relates to emergent phenomena, e.g., flocking of Boids and traffic congestion.

The second submodule presents agent sensing and types of agent interaction, followed by an introduction to sub-models, neighborhoods, and cellular automata which we investigate in the second lab. We also analyze Schelling's segregation model to provide practical examples of feedback effects and path dependence. The third submodule focuses on social networks in ABMS. We introduce the mathematical motivation necessitating the use of graphs, different types of networks, network theories, centrality measurements, and network typologies. The lab introduces the student to contagion problems and applies the SIR model to investigate the propagation of viruses.

The fourth submodule introduces the theory of adaptive behavior and modeling concepts like fidelity and realism. The goal is to introduce the student to the challenging task of modeling heterogenous human-like decision-making. We provide a brief introduction to microeconomic theory and utility functions, which is complemented by examples of two agent-architectures, a need-based model (ASSOCC [26]) and a comprehension and adoption model (associative diffusion [27]). The lab presents the extended version of the prisoner's dilemma where the student explores and develops different behavioral strategies. The last sub-module presents different approaches and tools used in population generation for realistic agent populations and demonstrates how the student can use NetLogo for pseudo-random number generation.

3.3 Module 3: ABMS as Method and Tool

The third and final module introduces concepts related to applying ABMS as a research method and targets ILOs 5 and 6. This module assumes that the student has a fundamental understanding of how to develop ABMs of social systems from the first two modules. Module 3 is shorter and aims to give an overview of challenges and approaches to apply models rather than an in-depth understanding of any specific method. It does not include any labs, and the written assignment does not include any coding.

First, the module covers Verification and Validation (V&V). Since the student does not necessarily have a programing background, the V&V part includes basic bug-testing techniques and code hygiene. Next, the concepts of uncertainty analysis, sensitivity analysis, and robustness analysis are introduced. Finally, submodule 3.1 discusses methods for quantitative and qualitative model validation. After completing this submodule, students can describe why V&V of models is important, know methods for performing V&V, and understand challenges that arise when doing so.

The second submodule concerns communication of agent-based models, and in particular using the ODD protocol [28]. In addition to aiding modelers in the communication of their models, the protocol is a useful tool for conceptualizing and structuring models during the model creation phase [18], thus being valuable for the student even if they do not seek to publish their models in the future. The third module's written assignment consists of creating an ODD description of a specific model. Not only does creating an accurate and comprehensive ODD description require a thorough understanding of both the protocol and the explained model; it also requires the student to understand principles such as emergence, adaptation, and stochasticity, which are all included in the protocol.

Finally, we present and discuss real-world applications of ABMS, e.g., in modeling, logistics, epidemiology, agriculture, evacuation modeling, and criminology. A model that has been used in real-world decision-making is given as an example for each of the covered domains. The reason for concluding the course with this submodule is so that the student will be able to see the connections between what they've learned and what is being done in state-of-the-art models and research, facilitating it for students to find ways to apply and further develop their knowledge outside of the course.

3.4 Examination: Final Project

As intended by the research-based learning approach, it is the goal of this course to cover the entire inquiry process. The different steps were part of the individual modules and in the final project, we put these together to one coherent approach. Accordingly, the goal of the final project is to identify a problem that can be analyzed using ABM, to describe how simulation can be used to investigate and better understand this problem, and to develop a conceptual model that described how a simulation could work, i.e., agent types, stochastic processes, input and output data, model components etc. Following the example of scientific symposia, the students have to submit a scientific poster, a short report, and a description of their (conceptual) model.

4 A Research-based Approach to Teaching ABMS

The research-based teaching approach we pursue in this course is inspired by different approaches for engaging undergraduate students in inquiry proposed by Healey and Jenkins [29] (see Fig. 2). It consists of four steps, that provide the students with theories, techniques, and research they require to independently conduct own simulation studies.

Starting with a *research-oriented* perspective, students develop necessary skills and techniques in a problem-based fashion. This includes ABMS theories and a hands-on introduction to working with simulation frameworks. Following, a *research-led* perspective is chosen, where students learn about current research topics and different applications of ABMS, using case studies. As a third step, a *research-tutored* perspective is employed, where students actively find and critically discuss relevant research. The course concludes with a *research-based* perspective, where the student actively conducts research and applies their acquired knowledge in an own simulation study.

This approach facilitates the steep learning curve, which results from the fact that the students will start the course without any prior ABMS knowledge. Then, after only 6-8 weeks of studying, the students are encouraged to identify and formulate an own research question that can be addressed using ABMS, to develop a suitable model for addressing this question, and through this to actively conduct ABMS research.

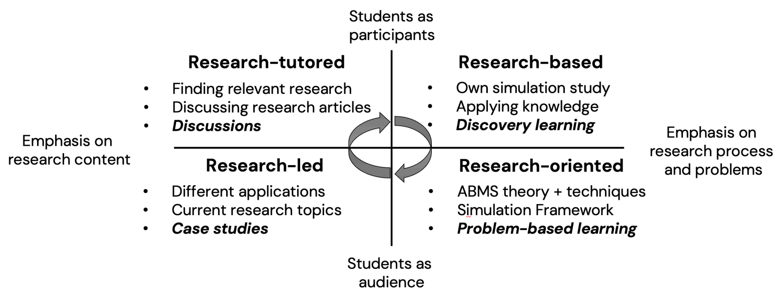

Fig. 2. Engaging students in research and inquiry, based on Healey and Jenkins [29].

5 Student Surveys and Course Evaluation

As part of the course, two student surveys[3] have been conducted. The first survey was sent out four weeks before the start of the course with the goal to get to know the students, to better understand their expectations, their preferred learning styles, and their previous knowledge. The second survey was sent out at the end of the course to assess the students' study experience, to analyze to what extent the students reached the ILOs, to give them the possibility to express their feedback, and to help us to further develop the course. Both surveys were conducted using an online tool, where link were sent out by email to all registered students. In both surveys, the participants were fully anonymous, and the system made sure that each student only could answer the survey once.

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[3] The questionnaires used for the surveys and the students' replies are shared upon request.

5.1 Pre-course survey

This course was given as an elective course for the first time, which is why there were no experiences from previous years. It was open for registration for any national and international student that fulfils the course requirements (general entry requirements for higher education and English proficiency). Thus, to get to know the students and to better meet their expectations, needs, and previous knowledge, we decided to send a pre-course survey to all 43 registered students. We received 28 replies (65%).

When asked why they have chosen to take this course now, 43% replied that this course sounded most interesting amongst the elective course, 36% attend the course voluntarily, 11% do research in this area, 11% take it in preparation for another course or program, and 4% need it for their job. Regarding the students' previous experiences and knowledge, 18% have attended courses on modeling and simulation, 14% on social systems and human behavior, and 11% on ABM. 71% of the respondents have not attended courses on these topics before. 18% of the respondents have previous used some simulation framework (e.g., Arena and AnyLogic) and none had used NetLogo before.

Finally, the students were asked which learning strategies work best for them. 54% want to work alone on assignments, 7% in groups, and 39% in a mixture of individual and group work. Even though the course was announced as 7.5 ECTS points[4] with a duration of 10 weeks (i.e., 20 hours per week), 39% of the students replied that they plan to spend between 5-10 hours per week on the course, 21% plan to spend 10-15 hours, and 32% plan to spend 15-20 hours. The results of the remaining questions that were asked in both the pre-course and the end-of-course survey are shown in Sec. 6.3.

5.2 End-of-course survey

After the course, we did a second survey to evaluate the students' learning. Of the 43 initially registered students, 36 actively used the learning platform, 23 completed the first assignment, and 13 of them also the final project. This corresponds to 36%[5] of the initially active students successfully completing the course.

First, the students were asked to what extent they have achieved each of the ILOs on a scale from 1 (very low extent) to 5 (very high extent). ILO1 was achieved to a high (4 of 5) or very high extent (5 of 5) by 92% of the students, ILO2 by 92%, ILO3 by 92%, ILO4 by 85%, ILO5 by 62%, and ILO6 by 54%. For none of the ILOs, any of the students assessed their achievement with less than 3 of 5.

85% say that the working methods and activities supported their learning to a high or very high extent and 85% state that the examination form allowed them to demonstrate how well their have achieved the ILOs to a high extent. When asked how many hours they spent on the course, 8% of the students spent 15-20 hours a week, 38% spent 10-15 hours, 31% spent 5-10 hours, and 23% less than 5 hours. The requirements to pass the course were assessed as "just right" by all students expect for one.

4 In Sweden, 1 ECTS credit corresponds to 26.66 hours of student work load.

5 Sweden does not charge tuition fees, which leads to a high number of students (ca. 34%) that only study elective courses, e.g., alongside their job. We assume this is a contributing factor to the relatively high dropout rates, which are similar to other elective courses.

5.3 Student development throughout the course

Some questions were part of both questionnaires to assess the students' development by comparing their knowledge, skills, and mindset before and after the course. As the questionnaires were anonymous, we cannot evaluate the students' individual development. Still, conclusions regarding the students' learning progress can be drawn.

In the pre-survey, most students stated that they want to learn about ABM (82%) and social systems (75%), followed by simulation and human behavior (both 64%). After the course, the number of students that have learned about the different aspects to a high or very high extent is 100% for ABM, 83% for social systems, 67% for human behavior, and 92% for simulation. 83% state they have learned about the link between these aspects to a high or very high extent.

The anticipated context of use for what they have learned in this course shifted. Potential use in research (from 11% to 38%), other courses (11% to 31%), decision support (29% to 46%), and work (32% to 46%) have increased significantly. Both teaching (11% to 15%) and not having use of it (29% to 31%) only increased slightly.

When comparing the students' skills before and after the course, we see an increase in programing (39% to 53% with high and very high knowledge), data analysis (from 36% to 46%), modelling (11% to 70%), analyzing human behavior (14% to 46%), and analyzing social networks (32% to 62%). Acquiring programming and data analysis was not explicitly goal of this course, thus, this increase might serve as an indicator which students successfully completed the course. Another possible explanation is that the labs help the students to improve these skills.

Regarding ILO fulfillment, we also see significant increases. The high and very high ability to explain what ABMS is increased from 14% to 92%, the use of ABMS to analyze social systems from 4% to 77%, the ability to implement ABMs from 11% to 62%, to design simulation experiments from 14% to 62%, to assess the suitability of applying simulations for a given question from 7% to 70%, and the ability to analyze simulation results from 7% to 62%. While around 60% to 90% stated that they had very low to low knowledge on the different ILOs in the post course survey, no student assessed their own knowledge on any of the ILOs as low or very low after the course.

Before the start of the course, students evenly estimated they will spend between 5 up to 20 hours. After the course, however, we see that most students spent less hours than they initially thought with the majority spending between 5 to 15 hours a week.

When comparing the study experience, we see a shift towards more senior students from before to after the course. Both questionnaires were sent out during the same term, so that we expected similar distributions. Instead, we see an increase in those students that have studied for 10 or more terms from 21% to 38% as well as a decrease in the group students that have studied for 5-6 terms from 46% to 38%. The other groups are almost unchanged, from which we can infer drop-out students.

Finally, we repeated the questions about the study discipline. Here we see a significant increase in natural science (14% to 46%), humanities (14% to 23%), and culture/design (4% to 8%) but also a decrease in social sciences (14% to 8%), economics (21% to 0%), and law (4% to 0%). The ratio of students from technology was the same (68% and 69%).

6 Discussion and Conclusions

This paper presents and discusses our experiences from developing an undergraduate course on ABMS of social systems. Rather than proposing how such a course should be structured and held, we discuss the feasibility of the research-based learning approach we pursued. Our goal is to inspire other researchers and teachers to develop similar courses, to address the lack of full-time courses, to establish a general curriculum, and to promote ABMS in undergraduate education.

We could observe a broad interest in ABMS of social systems, given the variety in students' backgrounds. Yet, it seems that most students chose the course due to specific aspects that are covered. Students have discovered the wide application range of ABMS, where we saw an increase in potential uses in research, work, and decision support after the course. A remaining challenge is to convey practical skills, i.e., model development, experimentation, and result analysis. Almost all students assess that they have gained high knowledge on what ABMS is and when it can be applied, however, only two-thirds assess their practical ABMS skills as high. Finally, we observed a drop-off of students with backgrounds in economics, law, and social sciences, disciplines, where ABMS can be of great value, yet, we can only speculate about the reasons.

The benefits resulting from the research-based approach include a high motivation and engagement from the students, shifting their role in the course from consumers to knowledge creators. It also promotes a symmetric teacher-student relationship and a deeper understanding of the subject rather than memorizing facts. Yet, there are also challenges related to this learning approach. This includes that the approach requires a high intrinsic motivation of the learners due to self-study approach and because of the is comparatively steep learning. Because of this, it is also more challenging for the teachers to identify students that need support in their learning. Since there was no preceding course that was run using another learning approach, it is difficult to assess to what extent the choice of research-based learning contributed to the students' success.

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