UiT The Arctic University of Norway

Faculty of Bioscience, Fisheries and Economics

Foundations of GAM Research

Methodological Guidelines for Designing and Conducting Research that Combines Games and Agent-based Models

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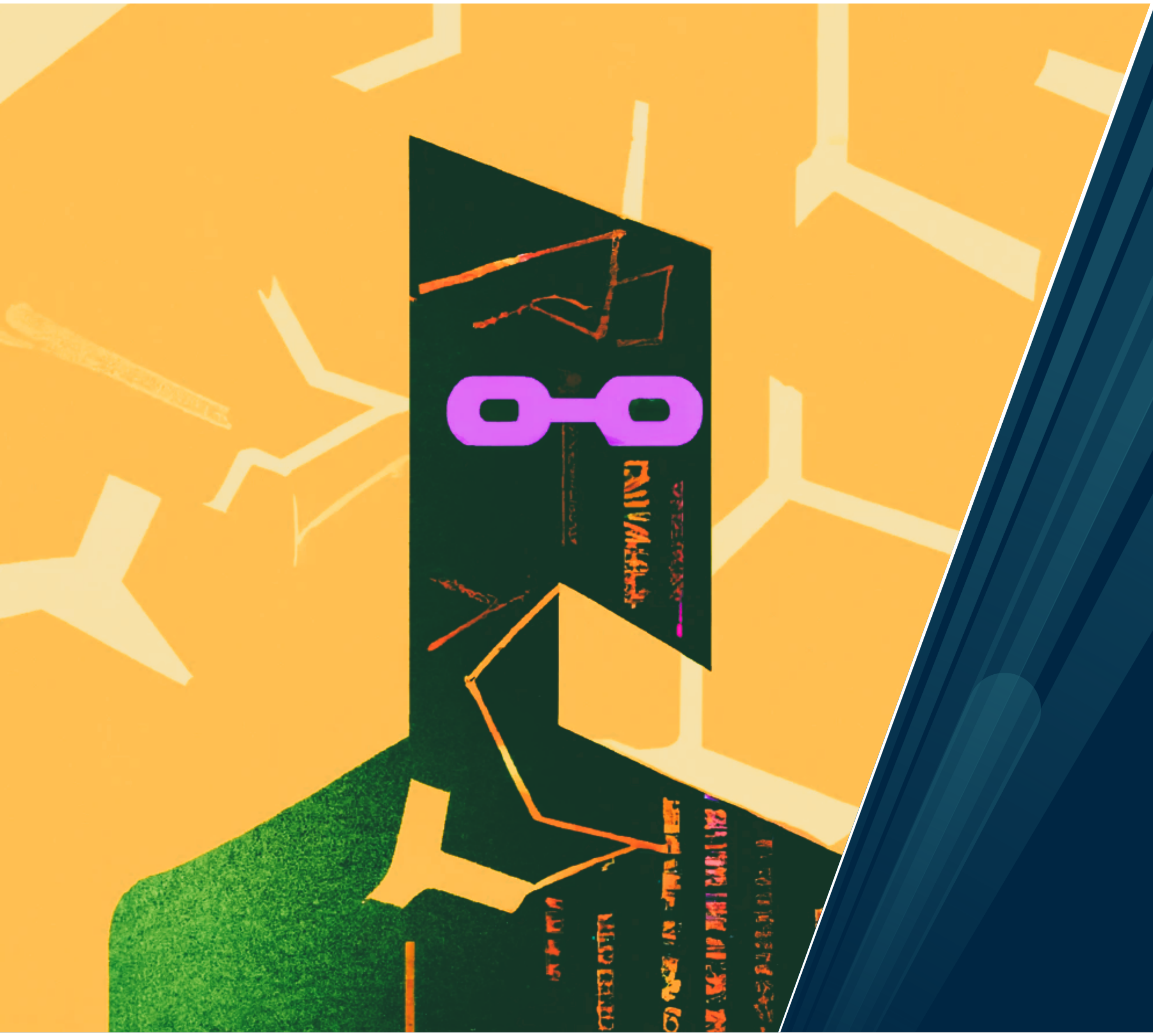

“The story starts with a battle that is not a battle, and ends with a game that is not a game”.
(Iain M. Banks - The Player of Games)

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Timo

Abstract

This thesis presents the development of the games and agent-based model methodology and provides methodological guidelines for using GAM research, i.e., combining games and agent-based models in research.

GAM research is rooted in complexity sciences and transdisciplinary research, offering valuable insights into complex, adaptable systems. GAM research has particular relevance in decision-making and complex-system management, thus fostering collaboration among scientists and non-academics from various disciplines. It is an engaging platform for data collection and stakeholder processes, thus enriching causal explanations. It should be noted that GAM research has the potential to overcome the limitations of traditional methods by facilitating hypothesis testing with simulation-based observations of human behaviours. Investigations in GAM research can change how social science addresses pressing global challenges. The immersive nature of games combined with agent-based models offers an innovative approach that attracts diverse participants, making it a promising tool for science that reaches beyond the classic academic spheres.

As a comprehensive handbook, this thesis offers researchers inspiration and references for conducting GAM research across diverse application domains. This thesis presents an assessment of the state of research that combines games and agent-based models and proposes a structured approach to making progress in this field. Addressing the lack of a standardised methodology, this thesis is aimed at improving research practices, transparency, and replicability. Practical advice is provided for guiding researchers through designing and conducting GAM research, thus promoting rigorous and comprehensive studies.

List of Papers

Antosz, P., Szczepanska, T., Bouman, L., Polhill, G. & Jager, W. (2022). Sensemaking of causality in agent-based models. *International Journal of Social Research Methodology*, 25:4, 557-567. https://doi.org/10.1080/13645579.2022.2049510

Szczepanska, T., Antosz, P., Berndt, J., Borit, M., Chattoe-Brown, E., Mehryar, S., Meyer, R., Onggo, S. & Verhagen, H. (2022a). GAM on! Six ways to explore social complexity by combining games and agent-based models. *International Journal of Social Research Methodology*, 25:4, 541-555. https://doi.org/10.1080/13645579.2022.2050119

Szczepanska, T., Angourakis, A., Graham, S., Borit, M. (2022b). Quantum Leaper: A Methodology Journey From a Model in NetLogo to a Game in Unity. In Czupryna, M., Kamiński, B. (Eds.) *Advances in Social Simulation. Springer Proceedings in Complexity.* Springer, Cham. https://doi.org/10.1007/978-3-030-92843-8_15

Contributions (in alphabetical order by first name)

	Paper 1	**Paper 2**	**Paper 3**	**Synthesis**
Concept and idea	PA, *TS*	ECB, HV, JOB, MB, PA, RM, SM, SO, *TS*	MB, *TS*	*TS*
Study design and methods	PA, *TS*	HV, PA, MB, *TS*	MB, *TS*	*TS*
Data gathering, analysis and interpretation	PA, GP, LB, *TS*, WJ	ECB, HV, JOB, MB, PA, RM, SM, SO, *TS*	AA, MB, SG, *TS*	*TS*
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MB - Melania Borit
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RM - Ruth Meyer
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TS - Timo Szczepanska
WJ - Wander Jager

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List of Abbreviations

Abbreviation	Meaning
ABM	agent-based modelling
ABG	agent-based game
API	application programming interface
AR	augmented reality
CAS	complex-adaptive system
CFD	conceptual framework development
CNA	co-occurrence network analysis
CS	complex system
CSS	co-self-study
DS	descriptive statistics
GAM	games and agent-based models
GAM DS	GAM documentation scheme
GAM research	research combining games and agent-based models
GAM RF	GAM reflection framework
GMABS	games and multi-agent-based simulation
IBM	individual-based modelling
MAS	multi-agent simulation
NLR	narrative literature review
ODD	overview, design concepts, details
RAT	rigour and transparency
RDT	research design type
RPG	role playing game
SECAS	socio-ecological complex adaptive system
SDG	sustainable development goal
SLR	systematic literature review
SNA	social network analysis
STS	socio-technical system
VR	virtual reality
QL	Quantum Leaper

1. Introduction

This PhD thesis presents the development of the **games and agent-based model methodology**, i.e., methodological guidelines for designing and conducting research combining games and agent-based models (i.e., GAM research). GAM research is an interdisciplinary approach that combines games and agent-based models to investigate complex dynamic systems.[1] GAM research involves the use of human participants, computer simulations, and projections to expand knowledge and address challenges that are difficult to address using other methods. This is especially true for dynamic social systems wherein individual actions can significantly impact the system's overall behaviour.

GAM is a unique approach that offers various ways of representing, exploring and studying these systems depending on the correspondence between the game and agent-based model components and the research design employed. The research designs used in GAM research are typically sophisticated and demand a high degree of cooperation between practitioners with diverse disciplinary backgrounds and skills. Participants in GAM research have the opportunity to discuss real-life challenges and enhance their problem-solving abilities by engaging in gameplay. Moreover, integrated GAM applications allow players to interact directly within a simulation model, which facilitates a deeper understanding of the target system as they explore and playtest different strategies. The strengths of GAM research lie in the integration of agent-based models and games. The agent-based model component is highly regarded for its ability to represent complex systems and create alternative scenarios, while the game component serves as a platform for interactive engagements. This integration allows for the development of context-specific behavioural agent-based models and the validation of models by comparing player behaviours with those of computational agents. Furthermore, owing to the participatory and engaging nature of GAM research, its reach extends beyond academia, and has the potential to attract a wide audience and foster great interest and involvement.

Over the last two decades, the popularity of research that combines games and agent-based models has grown. Although this research was performed in many application domains, and examples of applications can be found in the literature, an overarching methodological

[1] GAM research is not related to game theory.

integration that systematises the field and guides upcoming efforts is still lacking. In the four years of my PhD project, I undertook this task by analysing and structuring present efforts, identifying research gaps, and designing tools to improve the rigour, transparency, and replicability[2] of GAM research. The primary audience of this thesis is researchers and practitioners who intend to conduct GAM research. These individuals may be experienced or novice academics from the field of agent-based modelling (ABM) or game research who are searching for guidance. Policymakers and practitioners may find this thesis helpful as it presents theoretical and historical foundations and provides practical guidance for designing and conducting GAM research. For those interested in GAM research, the thesis clarifies what games are, what agent-based models are, and what they can provide, individually and when combined in GAM research.

The main aim of this thesis is to *develop a methodology for designing and conducting GAM research*. To achieve this goal, I formulated seven research goals (RGs), which are presented in Figure 1. My PhD research comprises three published articles and a thesis (this current text, also called a synthesis).

RG1: Conceptualise the nature of GAM research.
RG2: Describe the theoretical foundations of GAM research.
RG3: Describe the historical foundations of GAM research.
RG4: Identify prototypical research designs of GAM research.
RG5: Design tools to facilitate rigour and transparency in GAM research.
RG6: Demonstrate the usefulness of the developed methodological guidelines with an example of a GAM research design.
RG7: Reflect on the status of the methodological guidelines and suggest future steps for improving the GAM methodology.

[2] Replicability refers to the concept that different teams can arrive at the same results using the original author's methods and data (Barba, 2018).

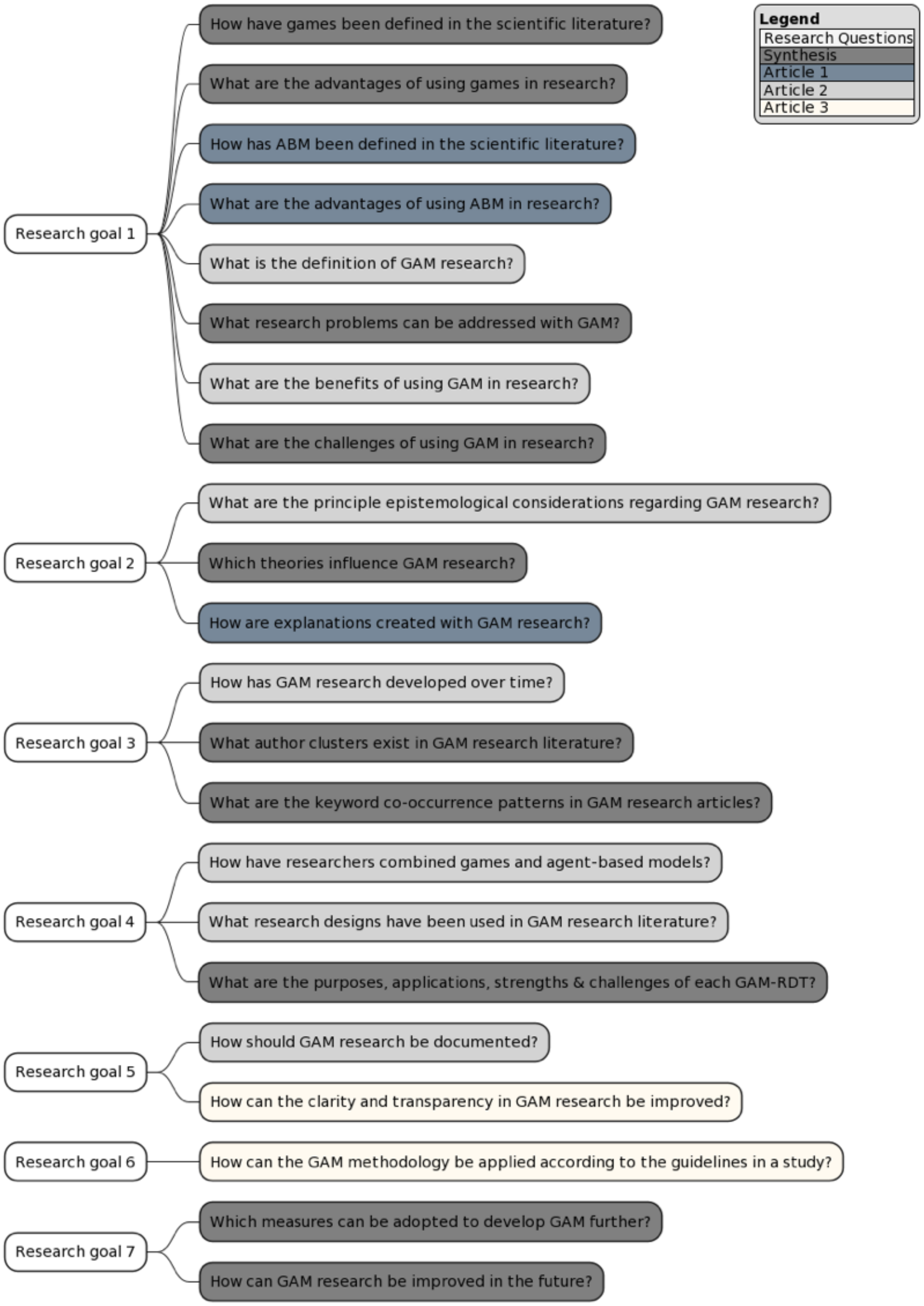


Figure 1 Overview of Research Goals, Research Questions, and Related Publications. In the legend, "Synthesis" refers to this PhD thesis, "Article1" refers to Antosz et al. (2022), "Article 2" refers to Szczepanska et al. (2022a), and "Article 3" refers to Szczepanska et al. (2022b).

The remainder of this thesis is organised in seven sections. Section 2 presents an in-depth discussion of the research methods used during my PhD and provides an overview of how they are connected to the research questions. Sections 3–6 are organised alongside the aforementioned sub-goals. They present and discuss the results of my PhD study. These three sections are written in the style of a methodological handbook (inspired by Cresswell & Clark, 2017). Section 3 (Nature of GAM Research) defines the GAM research. For this, the two components (games and ABM) are introduced individually and in combination. Moreover, this section discusses the research questions GAM research is best suited for answering and its challenges. Section 4 (Foundations of GAM) examines the historical, philosophical, theoretical, historical, and critical backdrop of GAM research. Section 5 (Designing GAM Research) provides guidelines for designing and communicating GAM research. The section presents the development of six key GAM research design types while providing insights into their purpose, selection criteria, strengths, and challenges. In addition, this section presents two conceptual frameworks that researchers can employ to improve the clarity and transparency of GAM studies. The GAM documentation scheme (GAM DS) supports researchers in structuring and documenting their studies, while the GAM reflection framework enhances interdisciplinary collaboration in research teams. Section 6 (Example of a GAM Research Design) offers an in-depth demonstration of these guidelines in practice. The example comprises the use of a GAM research design that was employed in the field of archaeology. Finally, Section 7 (Conclusion and Future Work) summarises the thesis while highlighting key findings. It offers a final evaluation of the outcomes and conclusions of this research, presenting a clear picture of the contributions made to the field of GAM. Moreover, it provides suggestions for follow-up studies and highlights avenues to build upon and expand the current state of GAM research. Moreover, the section discusses the requirements and steps required to drive GAM research to reach its full potential.

2. Methods

This PhD thesis is a methodological interdisciplinary study; both qualitative and quantitative research methods in an integrative manner herein. The selected combination of methods enabled the consideration of different perspectives on the research topic to understand the phenomena under investigation better. To address the primary goal of this thesis, i.e., developing guidelines for designing and conducting GAM research, I implemented a complex multi-phase research design (Figure 2). Multi-phase research designs are valuable for addressing incremental research questions that advance one research objective sequentially (Cresswell & Clark, 2017). The remainder of this section describes the methods and analytical techniques used. Reflections regarding each method are presented at the end of each section.

2.1. Narrative Literature Reviews

A literature review is a comprehensive and sometimes systematic examination of the existing research on a particular topic (Snyder, 2019). Reviews are an essential part of the scientific process as they synthesise existing bodies of knowledge to provide a detailed overview of the existing field. The primary purpose of a literature review is to collect, review, and evaluate the current research, assess its quality, and identify research gaps. As such, literature reviews have built the foundation for advancing knowledge and facilitating theory development (Webster & Watson, 2002). Existing guidelines for conducting literature reviews suggest the use of different types of reviews, such as systematic reviews and meta-analyses (Bearman et al., 2012; Davis et al., 2014), as well as semi-structured, structured, narrative, or integrative reviews (Baumeister & Leary, 1997; Wong et al., 2013; Demiris et al., 2019). Literature reviews have demonstrated great potential in making theoretical and practical contributions to research. However, the selection of a suitable review methodology is an essential step when conducting a literature review, and it depends on the purpose of the review in achieving the research goal. In this doctoral research, I used a narrative literature review (NLR) (Section 2.1) and a systematic literature review (SLR) (Section 2.2).

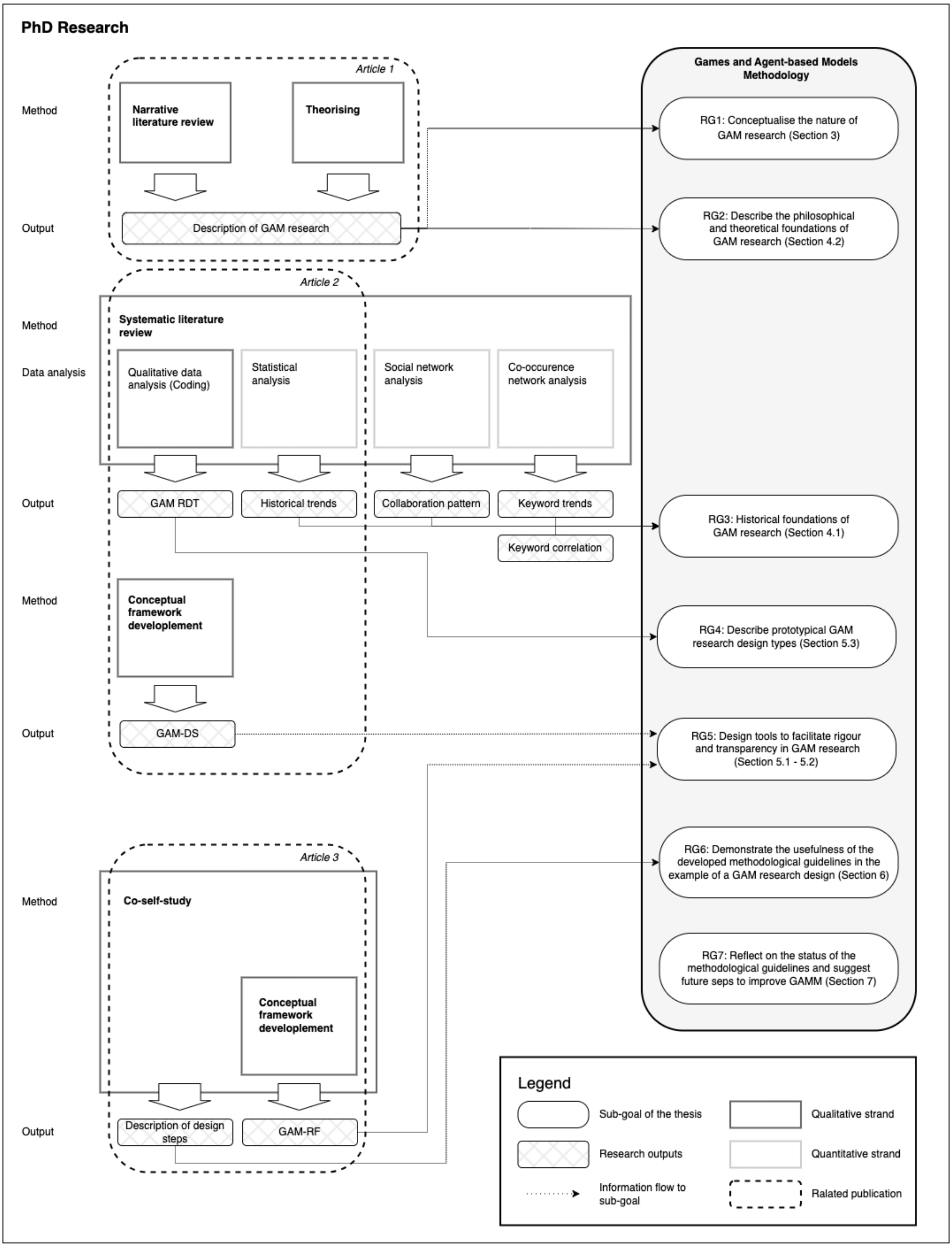


Figure 2 My PhD Research. The chart demonstrates the arrangement of the research methods in the multi-phase design of this PhD. The left side presents the four research phases with related methods and created outputs. The right side presents an overview of the research goals.

The *NLR* is an unstructured approach to examining the existing literature on a given topic to identify the essential findings and themes (Baumeister & Leary, 1997). Its aim is to obtain an overview of the existing knowledge on a given topic, determine how research within a selected field has progressed over time, or determine how a topic has developed across different research traditions. These reviews are unstructured as they do not follow a specific search strategy, and the research steps are usually not reported in detail. Instead, the execution of these reviews depends on the experience and preferences of the author (Cipriani & Geddes, 2003).

In this thesis, I conducted an NLR to identify studies that discussed combinations of games and ABMs. The primary purpose of this review was to capture the state of GAM research, which would help to define research questions and keywords for a following systematic review. The NLR followed a four-step sequence: (1) the search for related studies in several online databases, including Google Scholar, ScienceDirect, Web of Science, Scopus, and ACM Digital Library; (2) reading articles and identifying common themes in articles on combinations of games and agent-based models in research; (3) identifying common keywords used in these studies as the baseline for additional investigation in the following SLR; and (4) providing a narrative summary of the findings to define the GAM research.

Method reflection: The NLR played a crucial role in capturing the current state of research and developing my initial understanding of GAM research. The research's scope and focus are inseparable from my experience as a researcher. For the past 6 years, I have worked with ABM in participatory contexts, first as a researcher and later as a PhD candidate. These experiences shaped my perception of research and what I perceive as relevant and high- or low-quality research.

2.2. Systematic Literature Review

The SRL is a rigorous and structured practice that is aimed at reducing bias in scientific literature review processes (Bearman et al., 2012). It follows defined rules in searching, reviewing, and analysing findings obtained from multiple sources of literature (Pati & Lorusso, 2017). SLRs help consolidate conclusions from various studies and arrive at a conclusion regarding what future research is required; they can be used to determine if an effect is consistent across studies or which study characteristics impact the phenomenon being studied.

SLRs were initially used in medical sciences, but in the past couple of decades, they have been successfully applied in various other domains, including natural resource management (Weber et al., 2019), business (González et al., 2010), software engineering (Šmite et al., 2010), and social simulation (Gu & Blackmore, 2015; Farias et al., 2019).Statistical methods, such as meta-analyses, are occasionally used to integrate the results of the reviewed studies (Davis et al., 2014). However, this is only possible if the included studies share statistical measures (e.g., in randomised controlled trials). More qualitative approaches SLRs (i.e., qualitative systematic reviews) are used to assess the quality and strength of the research and compare results (Greenhalgh et al., 2004; Grant & Booth, 2009). Such reviews use a systematic process to collect articles and then a qualitative approach to assess them.

Table 1 Search Strategy including Data Sources, Search Terms, and Inclusion Criteria

Data sources	*Expert knowledge:* selected articles known to team members. *Databases:* articles selected after an initial investigation into the quantity and quality of the search results and into the accessibility of an application programming interface to the research team: Scopus: www.scopus.com ScienceDirect: www.sciencedirect.com
Search terms	TITLE-ABS-KEY((*"gaming" OR "role playing game OR "serious game" OR "board game" OR "online game" OR "computer game"*) AND (*"agent based model" OR "agent based simulation" OR "individual based model" OR "individual based simulation"*))
Inclusion criteria	Articles in English. Published in a peer-reviewed journal, proceedings, or book. Application in the research domain. A game and an agent-based model were included (though they could be the same).

In my research, I used an SLR to reveal consistencies and inconsistencies in current research practices and identify areas that require further organisation. In particular, the aim of this SLR was to (1) identify general patterns in papers related to GAM, such as the frequency of publication over time, application domain, publication outlet, and authorship; (2) synthesise the existing research design types used to combine games and ABM applications; (3) describe the application areas of these design types, including their evolution over time, purpose, field, and collaboration practices; (4) propose a structured approach for documenting GAM research to increase transparency and reproducibility.

2.2.1. Search Strategy

The online database search was conducted using Scopus and ScienceDirect (Table 1). The process was automated with a (self-written) Python crawler. The crawler accessed the online platforms' APIs (Application Programming Interfaces) and collected articles with keyword combinations of games and ABM. It downloaded the articles and collected the metadata provided by the publisher, such as the authors, publication year, abstract, journal, keywords, and publication outlet. The source code of the crawler, including its search configuration and data collection, is available on GitHub[3].

The *screening* process of the SLR was performed with an interdisciplinary team of eight co-reviewers. Initially, the team harmonised the understanding of concepts and methods and defined the inclusion and exclusion criteria, e.g., the meaning of "game". The selected working definition included all game types (e.g., board games, computer games, and role-playing games) while excluding publications on game theory. The research team assessed 315 article abstracts for eligibility using predefined inclusion criteria. Of these, a full-text review was performed for 92 articles. Eventually, 52 articles met the criteria, were incorporated into the final sample, and were saved to a structured Excel data form. The 52 included articles were then analysed using the methods described in Section 2.2. The method used for implementing this search strategy of the SLR is described in detail by Szczepanska and colleagues (Szczepanska et al., 2022a).

Method reflection: This SLR was crucial to my development as a researcher. Through the implementation of this SLR, I learned to use a structured and reproducible method for conducting reviews, which helped me to extend my knowledge of GAM research extensively. This systematic approach can be reproduced to re-evaluate my findings and continuously expand the knowledge base of GAM research. An unintended personal benefit of the SLR was that I extended my scientific network because I networked with many researchers who were interested in GAM. Moreover, the review allowed me to apply and extend my

[3] Link to the source code: https://github.com/tmrmn/Literature-research

programming skills in a new programming language. My research colleagues used the tool I created to conduct their own SLR.

A general limitation of the SLR method is that its results depend on how articles are collected in the literature selection process. Therefore, the results of the SLR should not be generalised without caution as the selected search terms, databases, and data collection period influence them. While the Python crawler minimises potential errors in the data collection, it only searched for publications in two online catalogues at a specific time. Other risks of distorting the results of the SLR arise from the inclusion and exclusion decision made by reviewing researchers. Although the team worked with a clear definition of the inclusion criteria, the final decision in such cases is always based on "subjective" interpretations of the responsible reviewer.

2.2.2. Data Analysis Strategy

The analysis of the 52 articles selected during the SLR comprises four strands: qualitative data analysis with coding, use of quantitative analysis techniques with descriptive statistics, co-occurrence network analysis (CNA), and social network analysis (SNA). The use of this mix of analytical approaches allowed me to acquire an in-depth knowledge of the history and current state of the field. It provided a nuanced overview of different research areas and contributions, aided in identifying gaps in the existing literature, and identified possible future research contributions.

2.2.2.1. Coding

Codes are descriptive labels that assign a symbolic meaning to the coded information. A *code* is a term created by the researcher to represent or explain the data by assigning it to a specific piece of data, i.e., a sentence of a journal article (Vogt et al., 2014). The collected codes aid in identifying patterns, categorising information and developing theories, and are used for conducting other follow-up analytical tasks (Miles, 2019). The codes developed for this study were aimed at identifying various methods of performing GAM research. The coding process is described in detail in Szczepanska et al. (2022a).

Method reflection: Coding taught me a valuable lesson in collaboration with an interdisciplinary team of scientists at both the conceptual and implementation levels. The process of managing a large co-author team taught me the importance of directing the group towards a specific goal while considering each researcher's unique needs and perspectives. When working in such a team, team members have different expectations about the results and ideas for approaching research tasks. For a novice scientist, understanding that co-authors may have varying working habits and time constraints that affect their ability to prioritise contributions to a research project was a valuable learning experience.

It was challenging to achieve a mutual understanding between multiple coders regarding the meaning of specific codes in the codebook and how to apply them systematically. The language in research publications is not 100% accurate. Researchers may initially code text passages differently depending on their disciplinary background expertise with qualitative research and coding. While the group size required extensive coordination and time for streamlining the coding, this process positively impacted the quality of the research results. While calibrating the process with a smaller group of coders may be more straightforward, the benefit of calibrating the coding within a large group is that it forces the researchers to undertake more detailed reflection on the code descriptions, describe the coding procedures, and establish control mechanisms.

2.2.2.2. Descriptive Statistics

Descriptive statistics are a means of organising and summarising large amounts of data. They provide the basis for interpretation, which results in a better understanding of the characteristics, patterns, and trends of the dataset (Holcomb, 2016). For this PhD, descriptive statistics were used to analyse the coding results obtained in the SLR analysis step. Therefore, the relationship between two or three variables was analysed, e.g., the relationship between the article publication years, application domains, and methods of performing GAM research was captured. Plots were then created to visualise the relationship between pairs of variables: frequency polygons, histograms, and bar charts. All the statistics and graphs were created in SPSS Statistics 26.0.0.0 and Microsoft Excel 365.

Method reflection: Descriptive statistics were applied to examine trends and patterns in GAM research. A limitation of the generalisability of the approach is the relatively small sample size of articles, which could result in an incomplete representation of the GAM field. Moreover, the analysis was limited to only three variables, while ignoring other potential patterns or trends that could have been uncovered through the use of a more advanced statistical method.

2.2.2.3. Co-occurrence Network Analysis of Author Keywords

CNA facilitates bibliometric research by analysing scientific collaborations, citations, co-cited references, and keyword co-occurrences (Van Eck & Waltman, 2014). In keyword co-occurrence analysis, the pattern between used keywords is examined and the evolution of their application over time is traced. Keywords can be collected from paper titles, abstracts, or author keywords (Choi et al., 2011; Zhao et al., 2018).

The CNA of the author keywords of articles included in the study of Szczepanska et al. (2022a) was performed using the Bibliometrix R package (Aria & Cuccurullo, 2017). This CNA is an additional research step of the synopsis and is designed to enhance the understanding of the dataset characteristics by tracking keyword frequencies over time and illustrating relationships among keywords.

Initially, author-defined terms having similar meanings were grouped (e.g., participatory method and participatory approach, ABM, and agent-based simulation) and plotted over the publication year to track emerging trends. Next, standardised keywords were developed. This step was necessary because publications from different application domains used different keywords to refer to the same concept. The standardised keywords were also used to characterise a minority of papers that did not include author keywords. Finally, a matrix was created to identify the relationships between keywords. A cell array b_{ij} *was used to* represent the number of articles that comprised the use of both keywords *i* and *j*, while the diagonal cells contained the number of articles that comprised the use of the keyword *i*. Each keyword was visually depicted as a node in the co-occurrence network graph. The font size of each node corresponds to the number of papers comprising the use of the keyword (i.e., b_{ij} for keyword *i*). Two nodes are linked if they co-occur in at least one paper. The thickness of the connecting link indicates the number of papers in which the paired keywords co-occur.

Method reflection: The CNA facilitated the discovery of connections between keywords in GAM research literature and supplemented the SLR with quantitative results. In addition to the limitations of the sample size that I have previously addressed, this analysis may also be susceptible to a bias originating from the selection of keywords by article authors, which is influenced by their respective research domains and agendas. There is a potential risk that establishing standardised keywords could further reinforce this bias.

2.2.2.4. Social Network Analysis

SNA is a method used for studying the relationships and connections among individuals, organisations, or societies. An advantage of SNA is that it makes the interpretation of extensive literature collections more manageable (Cowhitt et al., 2020). It can be used to reveal key players, understand collaboration patterns, and identify potential areas for intervention or change.

In this study, SNA is used to perform a co-authorship analysis of researchers who (co-) authored the publications included in the SLR (Szczepanska et al., 2022a). The SNA was performed using Gephi 0.9.2. The SNA is an additional analysis step of this thesis and is aimed at identifying the clusters of researchers existing in the GAM field and determining their activity over time and what GAM designs they predominantly used. The results of the SNA provide an overview of the GAM field by identifying existing efforts of research groups, their purposes, and contexts. Furthermore, the SNA offers a framework for identifying key players and understanding collaboration patterns. The results thus obtained are visualised as co-authorship collaboration clusters, i.e., teams of scholars who conduct research using GAM and publish the results together.

In order to identify authorship patterns, it was necessary to (1) define the study field of the author by matching the author‘s affiliation with the scientific field descriptors from the List of Descriptors of the Marie Skłodowska-Curie Actions (European Commission, n.d.), (2) classify authors as academic or non-academic based on their affiliation, and (3) assign a geographical location to the author based on the location of their affiliation. In the network visualisation, each author is represented by a node. The size of the node reflects the number of publications the person has authored. The larger the nodes, the greater the number of publications. Links between two authors indicate a co-authorship on the same publication. Thicker links indicate a strong collaboration between the first author and co-authors.

Method reflection: The SNA aided me in examining the structure and development of the GAM field over time. However, in a manner similar to other methods employed during the data analysis, the results are susceptible to selection biases in the sample. Moreover, the temporal representation in the network graphs may exhibit slight disparities compared to the actual changes in employment, geographical location, and collaborations, as it lacks time-dependent details owing to missing information. It is also important to note that the SNA only considered publishing authors, while other factors that could influence the growth of the field, such as administrative decisions and ongoing funding schemes, were not considered.

2.3. Co-self-Study

A self-study is a method used for examining one's self, in terms of one's actions and ideas (Hamilton & Pinnegar, 1998). Self-studies extend beyond mere introspection by critically examining how various external influences (such as literature, interactions with people, and exposure to ideas) relate to one's beliefs and experiences (Hamilton et al., 2008). They are aimed at revealing a researcher's professional identity and knowledge by focusing on one's practices and actions in relation to others. Co-self-study (CSS) emphasises the collaborative nature of the study. CSS is common in educational research wherein educators engage in ongoing dialogues and share access to their classrooms, students' feedback, and personal reflections (Coia & Taylor, 2009). This collaboration offers each participant support and challenges, thus allowing for the identification and refinement of commonalities while also promoting individual growth and development within the group (Butler & Branyon, 2020). Co-self-studies have a place in other research areas as the researcher's intellectual identity is formed within a dynamic continuum of relationships.

In my research, I employed CSS to gain insights into the applied practices of designing an application of GAM research. Details of this study are available in Szczepanska et al. (2022b). The GAM research exemplar that motivated this study was the *Quantum Leaper* (*QL*). This proof-of-concept video game was created using the Unity game engine and was based on the "Artificial Anasazi" ABM. The objective of the CSS was to make explicit the steps involved in designing and developing a particular type of GAM research. Moreover, it was aimed at reflecting on decisions taken and drawing conclusions to identify the design steps that could support practitioners in designing and conducting their studies. In order to achieve a satisfactory level of depth in the analysis, this CSS has been a joint effort between four researchers. The team consisted of Andreas Angourakis and Shawn Graham, the original developers of *QL* and both archaeologists; Melania Borit, who specialises in interdisciplinary research methodologies; and me, with a background in futures studies. All four team members have expertise in ABM and/or games/game design. Throughout the study, the researchers acquired insights and a deeper understanding of GAM research by sharing concrete experiences, exchanging thoughts and reflections about established practices, and questioning prevailing ideas/concepts within the collaborating team.

Method reflection: Initially, the third article of my PhD was aimed at deriving a normative step-by-step guide for designing and conducting research by analysing a GAM exemplar. Over the course of our collaborative effort, it became evident that crafting such a guide would necessitate clarification of and reflection on implicit concepts, processes, and ideas. This productive and exciting process prompted the team to engage in personal reflection and conceptualisations, thus enabling a deeper level of analysis. As a result, the team reached a conclusion that differed from their initial expectations.

2.4. Conceptual Framework Development

In a broad sense, a framework is a tool that aids in organising ideas by providing a foundation for thinking, communicating, and acting. Rapoport (1985) stated that frameworks are distinct from models and theories in that they do not describe or explain how things work. Instead, they facilitate thinking about phenomena, organising material, and revealing patterns. Ravich and Riggan (2016) defined a *conceptual framework* as an argument about the importance of a research topic in relation to the proposed method of studying it. It offers a method of connecting vital elements of the research process and illustrates how the research's purpose, questions, and design align with the study's objectives and contexts. While a conceptual framework can be theory-driven, descriptive, or causal, it is important that it includes the main cornerstones of the subject under consideration, i.e., key factors, variables/constructs, and the presumed relationship between them.

Given that GAM research is a relatively recent development, it is particularly vital to ensure clarity and transparency regarding the conceptual underpinnings of a methodology. The goal of the development of conceptual frameworks is to create tools that support GAM practitioners in structuring their research, reporting their studies, and improving the replicability of research studies in the GAM field and aligning them with the FAIR (findable, accessible, interoperable, and reusable) principles of Open Science (Wilkinson et al., 2016). During my thesis, two conceptual frameworks were developed. The *GAM DS,* published in Szczepanska et al. (2022a), guides the documentation of the GAM research design and execution to increase the reliability and credibility of publications. The *GAM Reflection Framework (GAM RF)*, published in Szczepanska et al. (2022b), supports the communication and structuring of the GAM development processes within interdisciplinary teams. The first step of developing GAM frameworks was to review the efforts presented in GAM related fields (such as ABM, games, and interdisciplinary studies). Subsequently, a customised framework was formulated to cater specifically to the requirements of GAM research.

Method reflection: The conceptual frameworks were developed because a review of the existing literature on GAM research revealed a common lack of explicitness regarding their conceptual and methodological foundations. This discovery prompted the effort to establish conceptual frameworks that address documentation and transparency challenges in GAM publication and aid interdisciplinary teams in overcoming communication barriers during the implementation of a study.

3. Nature of GAM Research

GAM research offers practitioners a distinctive approach to investigating complex dynamic systems, thus enabling them to represent and explore these systems in a unique manner. Depending on the selected research design (Section 5.3) and the correspondence between the game and ABM components, GAM research provides diverse avenues for accomplishing this goal. It can serve as a platform for participants to engage in discussions on real-life challenges and enhance their problem-solving skills by incorporating diverse knowledge into a target system via gameplay. Moreover, integrated GAM research applications enable players to interact directly within a simulation model, thus resulting in a deeper understanding of the simulated system through exploration and playtesting of various strategies.

GAM research leverages the strengths of its components. The ABM component is highly regarded for its potential to represent complex systems and create alternative scenarios, while the game component provides a platform for engagements. It should be noted that, both components of GAM can handle qualitative and quantitative data, with data flowing between the game and the agent-based model (Voinov & Bousquet, 2010; Salvini et al., 2016). A combination of both the components introduces the possibility of developing context-specific behavioural agent-based models or validating models by comparing player behaviours with those of computational agents. Another significant benefit of this combination is its ability to engage and reach a wider audience beyond academia, thus offering a fun and engaging participatory approach.

This brief overview highlights the potential of GAM research in addressing research problems. A more comprehensive representation is provided in subsequent sections. As in the case of any other research methodology, the GAM methodology is suitable for addressing particular research inquiries and entails both advantages and challenges. It is crucial for GAM practitioners, especially those new to GAM research, to grasp its nature. The following section is aimed at supporting researchers in the following:

- Defining GAM research, clarifying the concepts of games and ABM, examining their combined synergistic effects, and exploring their relevance in research.
- Recognising what research problems are best suited for GAM research.

- Understanding the advantages of using GAM research and acknowledging the challenges practitioners may come across when using GAM approaches.

3.1. Defining GAM Research

GAM research is an umbrella term that encompasses research approaches that blend games and ABM. To gain a clearer picture of GAM research, it is essential to clarify its core components—games and ABM—and how they contribute to scientific inquiries. Following this clarification, a definition of GAM research is provided.

3.1.1. Games

When you strip away the genre differences and technological complexities, all games share four defining traits: a goal, rules, a feedback system, and voluntary participation (McGonigal, 2011, p. 21).

Games manifest in various forms and types, spanning board, card, computer, and even pen-and-paper games. What various forms and types of games have in common is that they are something you play. However, establishing a precise definition for a game has proven to be a challenging endeavour. Various definitions of games have arisen over time, with each highlighting specific features. Nevertheless, there is no universally agreed-upon definition of games, and the question of what constitutes a game continues to be a fundamental issue within the realm of game studies.

Coleman (1969) outlined three characteristics of games. (1) Games have specific goals, which can either remain constant or change throughout the course of the game. (2) Games have a set of rules that dictate the permitted behaviours of the players. (3) Games have a set of rules that specify the consequences of each action the player takes, either helping or hindering their progress towards the goal. McFarlane (1971) further expanded this definition when introducing simulation games. Simulation games possess all the aforementioned traits and serve as abstractions or representations of complex real-life situations (Lukosch et al., 2018).

From a practical design perspective, games contain four basic elements: mechanics, story, aesthetics, and technology (Figure 3). This ensemble was referred to as the elemental tetrad by Schell (2019). Game mechanics comprise the procedures and rules governing a game. They describe the objectives, the ways players can and cannot achieve them, and the resulting consequences of player actions. The story entails the sequence of events within the game, which can be either linear and predefined or open and emergent. Aesthetics encompass the visual and sensory aspects of the games. They significantly impact the player's experience and are contingent upon the selected technology. Technology describes the materials and mechanics of the game, ranging from sophisticated digital options such as virtual reality and augmented reality to more elementary options such as dice, cards, or game boards. The selected technology determines the set of actions that are possible. However, while some game elements tend to be more visible than others in a given game, all elements within the tetrad remain interlinked and co-dependent (Schell, 2019).

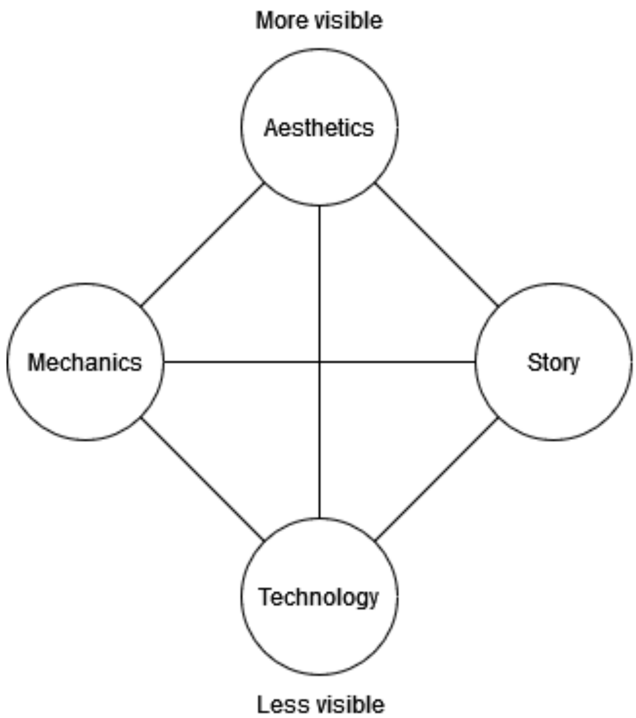


Figure 3 Four Basic Game Elements (From: Schell, 2019)

The definition of a game is often shaped by the technology used to develop the game and the intended purpose of the game. Different types of games adhere to their distinct logic and demand specific criteria for a comprehensive definition. For instance, the term "serious game" accentuates the seriousness (i.e., non-entertaining) and content-driven game attributes (accompanying the having-fun-driven aspects); the "role-playing game" underscores how the game's setting influences roles and behaviours of players; while a "simulation game" emphasises the simulation of real-world-activities (Abt, 1987; Michael & Chen, 2005; Susi et al., 2007).

The recent surge in the popularity of video games has resulted in the emergence of several new definitions. A review of 63 game definitions revealed different approaches to defining games: formal and strict definitions, incomplete conceptualisations, and approaches highlighting the game's purpose (Stenros, 2017). The expanding array of diverse game characterisations has added to the challenge of formulating an encompassing definition for games. Nonetheless, certain defining aspects are somewhat acknowledged. Juul (2005) highlights that all games are rule-based systems with variable and quantifiable outcomes, where (1) different outcomes are assigned different values, (2) the player exerts effort to influence the outcome and feels emotionally attached to it, and (3) the consequences of the game activity are negotiable.

Why is it worth implementing games in research? The gaming sector is expanding fast. By the end of 2022, the number of gamers worldwide had grown to an estimated 3.2 billion (Clement, 2022). To put this into perspective, it should be noted that the gaming industry's revenue of 196.8 billion USD in 2022 far exceeded the combined revenue of the movies and music industries (Wijman, 2022). Apart from their popularity and economic success, games have applications and traits that make them particularly interesting for scientists. Games can offer an artificial environment wherein players can take on specific roles and navigate a defined scenario (Barreteau, 2003). These imaginary game settings provide players with a space to explore, cooperate, or compete without facing real-life consequences (Adamatti et al., 2005; Perez Estrada et al., 2017). Some argue that games can effectively communicate the essence of a complex system better than traditional methods such as narration or visual aids (Miller & Cooper, 2021), as they can represent complex systems using underlying models that dictate processes, interactions, and game schedules (intended events and times). In recent years, technological advancements, such as virtual reality, augmented reality, touch interfaces, and other innovative input devices, have contributed to more immersive game experiences that blur the lines between the game world and reality (Marto & Gonçalves, 2022).

Within a gaming context, playing can be interpreted as a form of communication wherein players use a rule-based language to convey and receive messages (Duke, 1974). Furthermore, games can be used as a data-collection tool, offering insights into player behaviours and preferences via in-game analytics, surveys, and experiments conducted before, after, and during gameplay (Smith et al., 2015). For example, researchers can design games to mimic social interactions in a designated setting, which can be re-played, thus enabling subsequent analysis and tracking of player interactions.

When combining games with debriefing, researchers create a space for virtual experimentation and reflection wherein players (1) use the game as a playing field that allows them to try out alternative behaviours and test strategies and (2) use a debriefing session to reflect on their experience, identify areas for improvement, and develop strategies for future success (Fanning & Gaba, 2007). Debriefing is a tool used to boost long-lasting learning effects, particularly in the context of education. It encourages participants to reflect on their experiences and observations during the game, share insights, draw conclusions, and establish connections with other situations (Thatcher, 1990). In education, debriefing describes a process wherein participants talk about what happened during a learning activity, reflect on it, and integrate it into their understanding. In the field of simulation and gaming, debriefing has gained significant importance in improving the learning outcomes for game participants. The positive effects of debriefing and learning with games are often linked to Dave Kolb's (1984) experiential learning cycle wherein (1) action leads to knowledge and (2) knowledge enhances future action. According to Crookall (2010), the key to learning is not the game itself but the debriefing process instead, which involves analysing and reflecting on the game experience to transform it into meaningful learning.

The surge in the popularity of games among researchers parallels the increased public interest in gaming. Games have been used as a research device in human interactions (Verhagen et al., 2017; Vermillion et al., 2017; Marini et al., 2018) and as a method in science education (Ceberio et al., 2016; Szczepanska et al., 2020) and have been embraced as an innovative means of fostering social learning and collective decision-making, thus bolstering stakeholder engagement (Bakhanova et al., 2020). Furthermore, games have been employed to unveil new governance approaches for a more sustainable society (Gugerell & Zuidema, 2017) and convey research findings to broader audiences (Pfirman et al., 2020). Computer-assisted gaming has made significant progress in fields such as social studies, urban and land-use management, ecology education, international relations, healthcare, and natural resource management (Klabbers, 2006).

3.1.2. Agent-based Modelling

The second component of GAM research is ABM, a computational technique used for simulating the actions and interactions of autonomous software agents. In different research fields, different names are used to refer to this technique, such as individual-based modelling in ecology or multi-agent simulation in computer science. This thesis uses to a popular definition of ABM in the context of social simulation: ABM is a computational technique that has gained popularity across various social sciences; it entails the construction of a computational model that comprises agents, which serve as representations of actors within the social world, along with an environment wherein these agents operate. Agents are proactive and self-governing, which enables them to interact with each other and perceive their virtual world (Gilbert & Troitzsch, 2005).

A frequently highlighted characteristic of ABM is its explicitness at the micro-level, which forces the modeller to be precise and exact in specifying crucial elements and processes presumed to exist in the real world (Epstein, 2008; Gilbert, 2020). Another characteristic of agent-based models is that they allow researchers to perform in-silico experiments in the form of simulations. During a simulation, agents interact with one another by executing a given set of rules. These local interactions transpire within a bounded environment and result in emergent phenomena (Miller & Page, 2007). In this sense, an agent-based model can serve as a virtual laboratory that allows researchers to explore the simulated emerging patterns and track dynamic interactions between agents.

The concept of emergence, wherein complex patterns arise from simple rules, is a crucial aspect of ABM. ABM is often, but not exclusively, associated with a bottom-up approach (Heppenstall et al., 2011), thus indicating that actions at the micro-level are linked to emerging macro phenomena (Wilensky & Rand, 2015). The ABM approach to explanation broadly aligns with the mechanistic complex systems theory (Williamson, 2011; Antosz et al., 2022). This means that simulations run using agent-based models produce results based on underlining causal mechanisms that incorporate dynamic rules at the micro-level without a central planner that could influence a system outcome (Figure 4). By analysing the simulation results of an agent-based model, observed emergent macro-level phenomena can be rigidly related to the individual characteristics and behaviours of the implemented software agents.

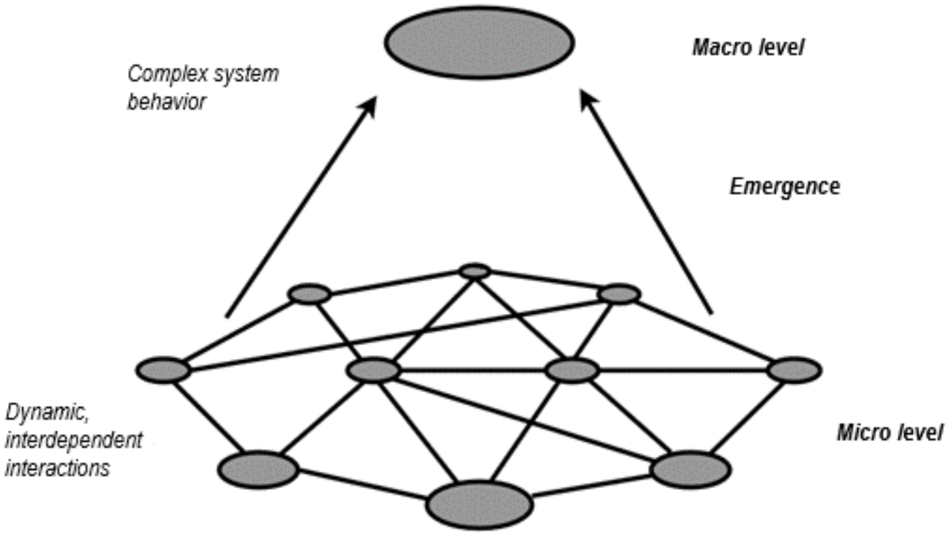


Figure 4 Complex System (Adapted from: Hilpert & Marchand, 2018)

What opportunities does ABM provide for researchers? Antosz et al. (2022), in the first article of this PhD thesis, argued that ABM is recognised as an interdisciplinary methodology that offers insights into the operations of complex, multilevel systems. It identifies ABM as a mechanism-based approach that represents causality by identifying the underlying mechanisms that generate the effects of interest (Hedström & Ylikoski, 2010; Hedström & Manzo, 2015) instead of providing a comprehensive account of all fragments of the full causal story (Elsenbroich, 2012). There has been increasing interest in ABM in social sciences as it allows researchers to build computational models wherein individual entities and their cognition and interactions are represented directly (Salgado & Gilbert, 2013). When modelling the emergence of social patterns using ABM, facts can be explained in terms of individuals' properties, actions, and relations (Pérez-González, 2020).

While ABM is commonly associated with bottom-up mechanisms and emergent macro-level effects, it has the potential to incorporate other types of causation (Antosz et al., 2022). ABM offers a path to overcoming "black-box" explanations, such as congruence-law or statistical explanations, by promoting mechanism-based explanations that reveal and describe the "cogs and wheels" underlying an investigated phenomenon (Hedström & Ylikoski, 2010). Formal models are crucial for achieving this breakthrough as they enable the connection between theoretical hypotheses as well as empirical validation and inter-subjective verification (Squazzoni, 2012).

A key strength of ABM is that it is well-suited for representing complex systems and can serve as an integrative platform for causal assumptions, thus providing researchers with insights into the functioning of a studied system (Antosz et al., 2022). Owing to their multi-level nature, agent-based simulations facilitate the observation of developments and patterns of upward and downward causation unfolding in a complex system. The ability to study the emergence of complex behaviours from simple actions in a simulation using ABM makes it an exciting approach for social sciences (Epstein & Axtell, 1996; Axelrod, 1997; Gilbert & Troitzsch, 2005). It allows researchers to establish verifiable causal relationships based on individual behaviour or interaction outcomes, which can be empirically verified (Squazzoni, 2014). Moreover, formal models encourage the reconsideration of the traditional assumption that complex social patterns always arise from complex individual causes. Instead, in many cases, social patterns may emerge from the cumulative effects of (simple) interactions over time.

Castellani et al. (2019) outlined the following three primary objectives of ABM in research. (1) It is used for theory development. For this, theories regarding the behaviour of individuals, households, or firms and their interactions are implemented in the model to test if it can generate the expected outcomes. (2) It is used for applied analyses, simulating potential interventions, counterfactuals, or future scenarios based on the results obtained from empirical research, and it informs decision-making. (3) It is used for stakeholder engagement. In stakeholder settings, the ABM functions as a tool for facilitating discussion, knowledge exchange, and reflection. Stakeholders and modellers explore and discuss their theories and beliefs about agent behaviours and their environment or the interventions they intend to employ. Another application of ABM is enhancing scenario processes as it enables researchers to systematically explore counterfactual scenarios by running multiple simulations to explore a parameter space and generate probabilistic outputs.

One field that has exhibited a growing interest in ABM is fisheries (Syed & Weber, 2018; Carrella et al., 2020; Haase et al., 2023), particularly small-scale fisheries (Bailey et al., 2019; Carrella et al., 2020; Lindkvist et al., 2020). ABM provides several advantages for exploring fisheries, which has been understood as a socio-ecological complex adaptive system

(SECAS) (Folke & Berkes, 1998; Ostrom, 2009), wherein traditional computational models have been criticised for their lack of sensitivity to the micro-level complexities (Weber et al., 2019) and their overly simplified representations of social dimensions (van Putten et al., 2012; Burgess et al., 2020).

In response to such critiques, the crafting of a sustainable fisheries management strategy must take into consideration a multitude of interconnections between (human) socio-cultural and (natural) ecological agents at both local and global levels (Levin et al., 2013). This is the area wherein ABM can truly excel: (1) ABM can aid in deriving conclusions regarding how different actors, such as fishers, traders, and fishing fleets, alter their behaviour based on their surroundings. (2) ABM can blend qualitative and quantitative data, thus further improving the understanding of the underlying processes. (3) ABM offers interactive and collaborative features, which allows stakeholders to exchange their knowledge, assumptions, and objectives. (4) ABM allows researchers to unite various forms of knowledge to comprehend how individual actions can result in larger-scale patterns and what interactions and processes may have caused a specific outcome (Lindkvist et al., 2020).

3.1.3. What is GAM Research?

The similarity between games and agent-based models makes combining both approaches a natural progression, which has well recognised in research over the last 20 years. Barreteau et al. (2001) called the idea of combining games and ABM an "obvious fit" because there is a remarkable correspondence between the elements of an ABM and those of a game, such as *agents and players, model rules and game rules, model time steps and game turns, and simulation runs and game sessions*. Some argue that a game, especially a computer game that enables players to create virtual worlds (e.g., "SIM City"), can be regarded as ABM with better graphics and less social theory (Gilbert, 2020). Similarly, an agent-based model can be considered as a computer game with theory-driven dynamics but without elaborate game design elements, such as game interfaces, player controls, dialogue systems, or general and visual storytelling. For this study, GAM research is defined as a multi- or mixed-method research design comprising at least one game and one ABM component. Either component can be used in a qualitative (e.g., as workshop tools or facilitation tools) or quantitative (e.g., to collect numerical data and simulate scenarios) manner.

As a result, GAM research encompasses four fundamental characteristics that each practitioner should recognise. A research design for a GAM study (1) includes at least one game and one agent-based model component, (2) combines the components in a sequential arrangement or by integration, (3) plans for data collection with both techniques (observation and simulation), and (4) explicitly describes the purpose, goals, and research question (see Sections 5.1 and 5.2). GAM research is often interdisciplinary because it depends on the cooperation between researchers having different scientific expertise. Over the past years, several methods of conducting GAM research that rely on different research processes, paradigms, and designs (e.g., games and multi-agent-based simulation (GMABS), conceptual modelling, participatory simulations, simulation games, and serious gaming) have emerged. The level of integration in the game and ABM arrangement is an essential factor to be taken into consideration.

In the second article submitted as part of this thesis, Szczepanska et al. (2022a) asserted that combining games and ABMs in a single research application enables researchers to leverage the individual strength of games and agent-based models and their synergies. While games involve interactions between multiple players who make decisions based on rules and objectives, ABMs use individual agents to simulate decision-making based on their own rules and objectives. By amalgamating these two approaches, researchers can capture the unique behaviour of human players and their interactions with software agents.

One way to better understand the nature of GAM research is to perform an SLR of published studies in journals (Szczepanska et al., 2022a). The following **list of** examples illustrates different rationales for combining games and agent-based models (from the SLR published in (Szczepanska et al., 2022b):

- Researchers employ GAM to simulate what-if scenarios. These scenarios are constructed by replicating gaming sessions and adjusting model parameters, attributes, and the scale of the game session. This could involve expanding the spatial scope, temporal dimensions, or number of players involved (Dumrongrojwatthana et al., 2011).
- Researchers use GAM to enhance the simulations of real-world systems. This is achieved by observing players and emulating their behaviours in the design of agents. The goal is to generate more precise and nuanced outcomes, mainly when the simulation incorporates rational and irrational agents (Cedeno-Mieles et al., 2020).

- Researchers employ GAM to dynamically gather data and validate model aspects by observing specific player behaviour and negotiating specific model rules with players. The form of the game usually aligns with its function. For instance, more open-ended game designs such as role-playing games (RPGs) serve to replay model dynamics and discuss them in an informal setting. Conversely, puzzle and board games often adopt controlled settings to monitor player behaviour and decisions (Shelton et al., 2018).
- Researchers use GAM to simulate dynamic feedback for players within the game environment. This could involve updating environmental or agent attributes as the game unfolds or providing generative properties for the game. Players respond to simulated environmental feedback that arises from their actions within the game (Ahlqvist et al., 2018).
- Researchers employ GAM to provide a platform for player engagement with a specific topic, thus enabling them to explore strategies for overcoming challenges (Salvini et al., 2016) or collaboratively develop potential development scenarios (Voinov et al., 2016).

3.2. What Research Questions are Suitable for GAM Research, and What are the Advantages of Using It?

To effectively use GAM, practitioners should employ it when it proves to be an appropriate method for addressing the given research problem. While GAM research has broad applicability across disciplines, it is important to acknowledge that not all research questions suit this approach. In many instances, other research methods could be more suitable for achieving the research objectives, given the considerable investment of time and resources required for a GAM study. It is thus worth determining when GAM research should be considered an appropriate choice. Given the diversity of games and ABMs, it is challenging to enumerate all the contexts in which GAM research can be valuable. However, there are certain problem characteristics that GAM can provide solutions for. More detailed descriptions of specific uses of GAM research depending on its design choices are provided in Section 5.3.

GAM research is suitable when researchers need to address a problem that occurs in a complex (adaptive) system.

A complex system describes a collection of elements that interact with each other in a disorderly manner, thus resulting in a robust organisation (Ladyman et al., 2013). System changes are considered as emergent phenomena resulting from upward and downward causation between the micro-level and macro-level. A complex adaptive system (CAS) is a complex system that has the capacity to change over time as it learns from previous experiences (Abbott & Hadžikadić, 2017). CAS is self-organising and driven by feedback loops, and it often exhibits non-linear change (Carmichael & Hadžikadić, 2019).

Understanding a CAS necessitates the study of the characteristics of the interplay and interactions of its elements; however, as the system- or macro-level outcomes of a CAS can be emergent, the observations of the interactions between the individual system elements alone may be insufficient (Edmonds & Meyer, 2017; Miller & Page, 2007). Moreover, owing to its self-organising properties, a CAS may work in counter-intuitive ways. It is particularly challenging to address problems occurring in a CAS because its behaviour is shaped by evolving processes that change over time. For example, changes in individuals' opinions, behaviours, and relationships can undergo shifts on varying timescales (Richardson et al., 2014). As a result, phases of relative stability can be followed by rapid system changes that trigger cascading causal feedback loops across multiple system levels (Jager & Ernst, 2017). Recent research has demonstrated that adopting a CAS perspective can elucidate the behaviour of complex dynamic systems, which supports problem-solving and decision-making processes (Siegenfeld & Bar-Yam, 2020; Liang et al., 2022).

GAM research has some characteristics that make it well-suited for addressing the challenges of problems that occur in CASs:

1. Researchers can use GAM research to represent the emergence of a CAS. A significant part of the analytical power of GAM research is obtained from ABM. ABM can represent the crucial, multi-level components of emergent phenomena. It serves as a platform for researchers to implement various causal relationships, thus allowing them to build more complete causal explanations by investigating how a multi-level phenomenon occurs through gameplay (Antosz et al., 2022).

2. GAM research can produce simulated what-if scenarios. Simulations enable researchers to test various problem-solving approaches in a virtual environment and obtain insights by analysing the simulated outcomes. Simulating the impact of problem-solving strategies demonstrated by players on the system facilitates learning through trial and error. Simulations are beneficial in situations wherein (1) implementing a solution to a problem is considered a one-shot operation, (2) suboptimal solutions can have negative unintended consequences (e.g., in policy implementation), or (3) the scenario or elements of a solution raise ethical concerns (e.g., crisis situations).
3. GAM research can be used to integrate a game with an agent-based model to form a socio-technical system that links human and computational actors (Baxter & Sommerville, 2011). By observing the interactions between players and agents, researchers can address uncertainties regarding real-world problems by anticipating and simulating the consequences of player inputs. This can help researchers to find the right balance of solutions in a game without causing unintended damage to the real-world system.
4. GAM research allows researchers to study human group dynamics and social behaviour in a controlled virtual environment wherein players interact within the game. Analysing the interactions and behaviours of groups of people can yield context-specific insights and a deeper understanding of causal links within the micro-level and between the micro and macro. Playing involves strategic interactions between decision-making entities. By studying these interactions, researchers gain insights into how individual choices and strategies shape the overall system behaviour. Games help capture the dynamics of decision-making, cooperation, competition, and coordination.
5. Simulation games can also be designed as an abstraction of complex real-life situations. Such a realistic setting increases the ecological validity (i.e., the ability to generalise study findings to the real world) of a GAM study by promoting situational awareness and allowing players to gain insights into complex systems (Section 3.1.1).

GAM research is suitable when researchers need to find solutions to wicked problems. Modern societies face a multitude of complex social challenges that have been labelled wicked problems, i.e., complex and difficult challenges that are difficult to define, have multiple possible solutions, and cannot be easily categorised (Rittel & Webber, 1973). Wicked problems arise primarily from three features: dynamic social complexity, uncertainty, and interest/value conflicts (Conklin, 2003). Even establishing a shared understanding or scope of a problem becomes a significant hurdle, which results in conflicts between groups having diverse and sometimes conflicting interests.

In research, disagreements may arise between stakeholders and scientists regarding the nature of the problem, potential solutions, or desired outcomes, thus hindering the development of effective planning policies for addressing the issue (Head, 2022). Five reasons were provided to explain why standardised analytical techniques fail to address wicked problems (Polhill et al., 2021): (1) there is no definitive formulation of a wicked problem, (2) there is no definite solution to a wicked problem as the solution may generate cascading effects and/or is a symptom of another problem, (3) there is no clear set of potential solutions nor a set of guidelines for what actions are considered acceptable or appropriate in tackling wicked problems, (4) the wicked problem can be explained in various ways, and (5) every wicked problem is unique. According to Andersson et al. (2014), understanding wicked systems is more effectively achieved through a narrative instead of simulation techniques alone. They emphasise the incorporation of narratives and participatory approaches for achieving more valuable outcomes when tackling wicked problems. Moreover, Davies et al. (2014) found that policy decision-making and strategy development for wicked problems are inadequate without the assistance of simulation and prediction.

GAM research has demonstrated several beneficial characteristics that make it a valuable tool for tackling wicked problems:

1. GAM research comprises narration, participation, and simulation, which are crucial for addressing wicked problems. Games offer the potential for generating narratives through storytelling, while ABM involved the creation of simulations of hypothetical what-if scenarios (future or past counterfactuals). The combination of these two elements allows researchers to create virtual settings wherein participant players do not have to imagine a situation but are immersed in a counterfactual reality.
2. GAM research enables researchers to address uncertainties by observing players' reactions and responses to simulated solutions and collecting player feedback in debriefing sessions. Both these components of GAM research are dynamic.
3. When both the nature of the problem and the response to the problem are uncertain, GAM research can be designed as an ongoing adaptive approach. In such an approach, uncertainties regarding a wicked problem are clarified by constantly improving an ABM

with feedback from stakeholders and experts during gaming sessions that aim to negotiate and improve model aspects.

4. In situations wherein the nature of the problem is agreed on, but it is unclear how to address the problem, GAM can be used to identify possible actions and solutions while simultaneously allowing players to learn about the impact of possible solutions in gaming sessions.
5. GAM research allows researchers to expand the knowledge collected through observation and feedback by simulating projections and calculating predictions, thus facilitating experimentation with different possible solutions for policy decision-making and strategy development.
6. GAM can be used to evaluate and expand simulations. In a game, players may perform actions that are inadequate or infeasible in the real world, thus expanding the simulations with novel and unexpected agent behaviours.

GAM research is suitable for problems that need to be addressed using transdisciplinary research

It has become evident that complex and wicked problems cannot be effectively tackled within conventional disciplinary boundaries. Tress et al. (2003) defined interdisciplinary studies as the collaborations of different unrelated academic disciplines with contrasting research paradigms to achieve a common research objective. Interdisciplinarity forces researchers to work across subject boundaries and merge qualitative and quantitative methods to harness knowledge and expertise from multiple disciplines, which leads to a more profound comprehension of complex issues and, subsequently, better solutions to problems. Transdisciplinarity expands the concept of interdisciplinarity by including non-academic participants in the research process (Tress et al., 2005). Transdisciplinary research works with three types of knowledge—systems knowledge (knowledge of the current status), target knowledge (knowledge about a target status), and transformation knowledge (knowledge about how to make the transition from the current to the target status)—and reflects their interdependence throughout the research process (Hadorn et al., 2008). By embracing transdisciplinary, researchers can better grasp the complexity of problems because they consider diverse scientific and societal perspectives, bridge the divide between abstract and specific knowledge, and create new knowledge in the process. The dialogue between researchers and stakeholders represents a new paradigm of scientific reputation, where science no longer solely provides a problem solution but develops socially robust knowledge

(Nowotny et al., 2001). Consequently, research is evaluated not only based on its scientific significance but also on the value it creates for society (Fecher et al., 2021).

GAM research has several beneficial characteristics that make it valuable for research questions that are required to be addressed with transdisciplinarity:

1. GAM research provides a framework for transdisciplinarity because it allows researchers to integrate diverse types of knowledge (i.e., academic and non-academic) into ABM and simulations to gain deeper insights into the nature of a problem.
2. GAM research is especially valuable when involving human stakeholders, experts, or other participants in the research process. Firstly, GAM research takes advantage of the widespread popularity of games, which enables researchers to engage larger groups of participants and enhance the quantity, relevance, and reliability of research data.
3. Games provide an engaging and motivating environment that improves participants' readiness to engage in the scientific process and minimises dropout rates. Many players invest multiple hours in playing and exploring games, thus providing researchers with the opportunity to collect data from numerous sources over an extended period.
4. When the data collection process in GAM research is based on the observation of player actions and therefore offers an advantage over methods that rely on self-reporting (e.g., in-depth interviews and surveys). Observational focus makes GAM research less susceptible to biased responses, self-enhancement, and outright lies. A well-designed game environment that closely resembles the real world can aid in obtaining an accurate understanding of human behaviour, as participants are more likely to act naturally.
5. The creation of engaging environments for players to engage in research processes can also encourage stakeholders to take a stake in the research process. This is particularly beneficial in participatory or action research, as it activates stakeholders and enhances the impact and sustainability of a study.

3.3. What are the Challenges of Using GAM Research?

GAM research can be instrumental in understanding and addressing research problems; however, conducting GAM research involves specific challenges. Researchers should be sensitive to the challenges of the approach and carefully consider if a GAM design is necessary for answering the research questions.

The challenge of skill: Practitioners planning to use GAM research need access to a large variety of skills, especially because ABM and games are not mainstream research methods and are, therefore, not commonly taught at universities. Finding researchers that are trained in both approaches can be rather difficult. The SLR conducted by Szczepanska et al. (2022a) demonstrated that the majority of experts in the domain of ABM conduct current GAM studies without the involvement of practitioners from game research. This results in GAM studies with well-thought-out ABM components but a less elaborate game component. When applying GAM research to specific application domains, collaboration between researchers becomes necessary for accessing the expert knowledge needed for successful GAM implementation.

The challenge of time: GAM research is a relatively time-intensive endeavour. The diverse demands of a GAM study (e.g., designing and developing games and simulations) can result in significant time investments. Researchers must ensure that the effort to conduct the study remains justifiable given the expected outcomes. Describing the details of the GAM methodology (i.e., this thesis) is a first step in streamlining the process of designing and conducting GAM research and will hopefully lead to more future guidelines that will facilitate reproducible GAM research designs.

The challenge of representing complex systems: Developing adequate representations of real-world complex systems poses another challenge in GAM research. A good simulation model needs to include all the relevant system elements, as the outputs of the simulation model are interlinked with its internal mechanical structures, such as rules, behaviours, interactions, network structures, and sequencing (Manzo, 2014). Oversimplifying the representation of phenomena with models that are too simple could lead to results that do not include essential influencing factors, while overly complex models tend to be less general

(Edmonds & Moss, 2005). There is an intrinsic challenge to GAM applications, which makes them sufficiently simple to be playable but sufficiently complex for adequate representation.

The challenge of playing games*:* The challenge of playing games is related to concerns regarding the validity of the results of a GAM study. Data collected in a game world and from a simulation could be challenged because it does not stem from the real world. Such concerns are related to the challenge of representing a complex system. Additionally, players are aware that they are playing. Playing might influence their behaviours, as players can strive to "beat" the setting instead of acting authentically as in a real-world context.

The challenge of transdisciplinary research*:* GAM fosters transdisciplinarity as it involves researchers from diverse backgrounds collaborating with diverse non-academic participants to co-create solutions. Transdisciplinarity research presents its own challenges (Lang et al., 2012). In GAM research, these challenges are especially prominent in two areas. Firstly, there is the difficulty of finding a sample of individuals who adequately represent all relevant stakeholders or experts. Moreover, communication issues may arise within the research team owing to diverse disciplinary backgrounds that can lead to unspecific definitions of concepts. GAM needs effective collaboration and clear communication between researchers. Standardisation (as suggested in Section 5.2) can improve the quality of GAM research by providing researchers with conceptual frameworks that aid in addressing common issues of transdisciplinary research. For example, communication barriers between researchers of different disciplinary backgrounds can result in unspecific definitions of concepts or insufficient documentation, thus hindering rigour and transparent research practices.

4. Foundations of GAM research

Before planning a GAM research study, researchers should lay a robust foundation by understanding the fundamentals of this type of research. This foundation serves two purposes: it helps researchers contextualise their study within the broader scientific landscape and provides a valuable frame of reference. This section presents the foundations of GAM research. It is aimed at providing researchers with a comprehensive overview of the historical developments and major research streams in the field (Section 4.1); the epistemological aspects of knowledge generation, including exploring the philosophical and theoretical foundations (Section 4.2); and the generation of knowledge and what philosophical and theoretical perspectives are involved in the process. Lastly, researchers should consider critical perspectives to GAM research to ensure their work does not perpetuate existing social injustices and discriminating practices (Section 4.3).

4.1. Historical Foundations

This section provides an overview of the historical foundations of the field of GAM research by categorising existing research efforts based on their purpose and application context. Furthermore, influential communities and recent developments and debates are identified. This section is aimed at equipping researchers with the knowledge required to connect their research to relevant literature and establish a rationale for applying GAM research in specific fields.

The information presented in this section draws from a sample collected via a previously conducted SLR (Szczepanska et al., 2022a), as described in Section 2.2. The overall historical patterns in GAM research were identified using a DS (Section 2.2.3.1). Further analysis of the data collected in the review was performed using CNA (Section 2.2.3.2) and SNA (Section 2.2.3.3). CNA was employed to link author keywords and uncover key themes in GAM research, while the SNA used metadata to visualise author networks and gain insights into existing research communities.

The evolution of GAM research: The combination of games with agent-based models for the purpose of research is a relatively new development. The first published article in the SLR sample (N = 52) is a participatory research design that employed an RPG to validate an agent-based model together with stakeholders (Barreteau et al., 2001). Over time, the popularity of combining games and agent-based models in research has grown, and its application domains have become widespread. In the period of 2001–2010, Szczepanska et al. (2022a) conducted an SLR and identified 14 publications, with the majority of them (72%) in the domain of natural resource management (Figure 5). The publication number increased almost threefold in the following decade (2011–2020). The slight downward trend in 2019 and 2020 could be an artefact of the data collection that was performed in February 2020. However, a subsequent scoping search covering the period from January 2021 to July 2023 shows a slight decline in publications (3 in 2021, 5 in 2022, and 1 in 2023). The same configuration of databases, search terms, and inclusion criteria was used in the scoping search as that in the original SLR (Table 1), which resulted in a population of 65 articles, of which nine studies matched the inclusion criteria (Appendix A: Selected Literature). Until 2021, the combination of games and ABMs was applied in 14 different fields, which demonstrates a high degree of flexibility. The most prominent application domain is natural resource management (54%), followed by group dynamics (14%), public health (6%), and city logistics (4%).

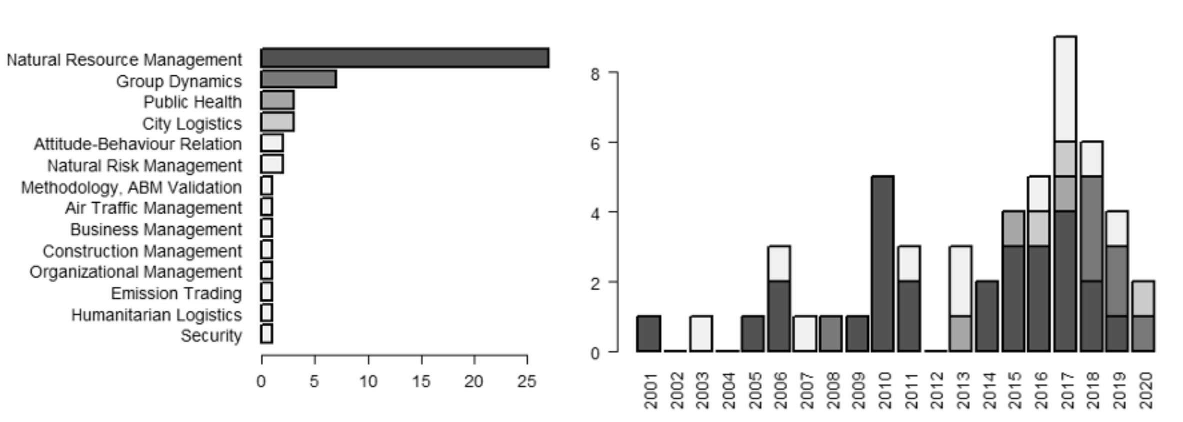


Figure 5 Distribution of Games and Agent-based Models Publications Over Time and Application Domain (Szczepanska et al., 2022a).

On analysing the frequency of the author keywords of publications included in the SLR published in Szczepanska et al. (2022a) over time, it can be observed that, since its beginning in natural resource management, the discussions surrounding GAM have become more diverse, new research fields have become involved, and new concepts and ideas have been introduced (Figure 6). This diversification could have been resulted from new research communities entering the field. One example is the term “serious game”, which has been appearing more frequently since 2017.

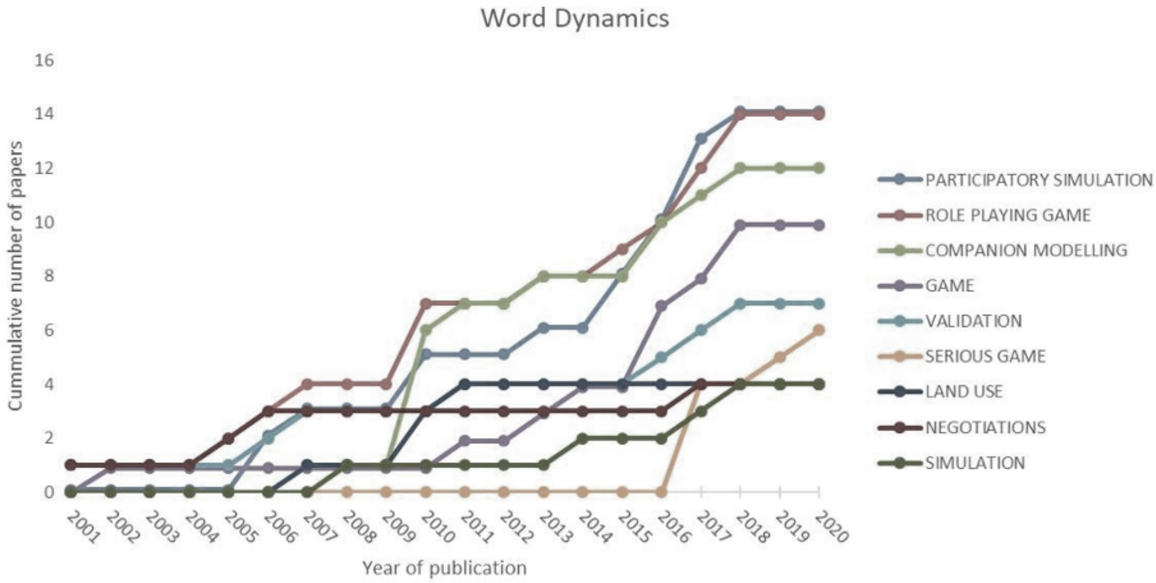


Figure 6 Keyword Dynamics of how Author Keywords are Used Over Time in the Publications Included in the SLR Published in Szczepanska et al. (2022a). The graph shows the most used keywords by count and year of publication.

Prominent concepts in GAM research: The CNA of the keywords of the publications included in the SLR published in Szczepanska et al. (2022a) exhibits a strong relationship between the nodes of the participatory simulation, the role-playing game, and agent-based model (Figure 7). These three elements form a complete subnetwork (a fully connected subset of nodes within the larger network of the author keywords) with thick edges (the thickness of their connecting edges indicates how often these keywords appeared together). A second subnetwork is formed between the companion modelling, role-playing game, and agent-based model. Both subnetworks are connected through a weak link between the participatory simulation and companion modelling.

The use of role-playing games and agent-based models is described by various definitions, typologies, workflows, and decision-making tools, as summarised in studies by Voinov and Bousquet (2010) as well as Voinov et al. (2016; 2018). In the context of natural resource management, also sometimes referred to as the GMABS methodology (Adamatti et al., 2005; Adamatti, 2009). Companion modelling, which was introduced by Castella and Verburg (2007), is associated with a stakeholder process that involves a combination of ABMs and role-playing games to co-design a system model. The method uses game elements to explore and formulate policies or influence decision-making processes with stakeholders.

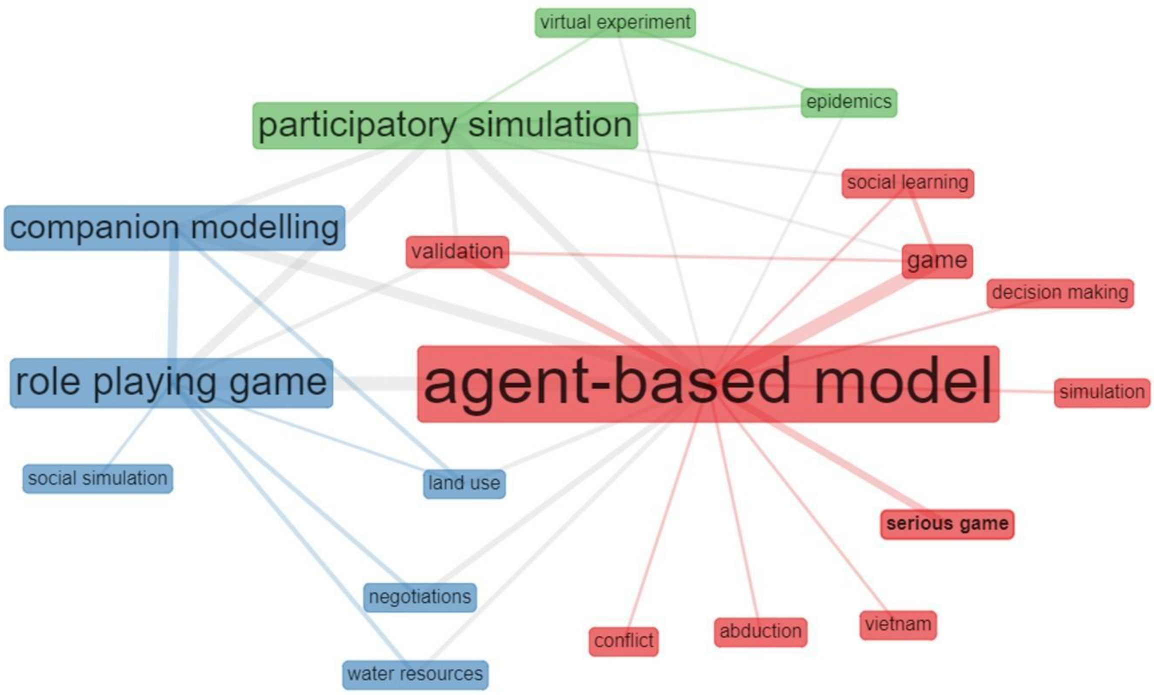


Figure 7 Co-occurrence Network Analysis of Author Keywords of the Publications Included in the SLR Published by Szczepanska et al. (2022a). The graph presents keywords as nodes. The font size used for a node corresponds to the frequency of the keyword in published papers. When two keywords appear together in at least one paper, they are linked by a line. The thickness of the line between two nodes indicates the number of papers in which the two keywords co-occur. Distinct colours represent different network clusters.

Participatory simulation, first coined by Guyot and Honidens (2006), was introduced to change the role of human players in role-playing games. Stakeholders could manipulate a dynamic system in the context of a game by taking over the control of some software agents. Every decision and interaction was registered for further analysis, but the players could not modify the settings and rules of the underlying model. Although the relationship between participatory simulation and companion modelling is close, the CNA highlighted some differences. Firstly, participatory simulation is typically used to foster or stimulate social learning (Becu et al., 2017; Le Page & Perrotton, 2017) and to conduct virtual experiments (Delaney et al., 2013; Kleczkowski et al., 2015), while role-playing games are often associated with social simulation (Nguyen-Duc & Drogoul, 2007; Dubois et al., 2013) and are used to support negotiations (Barreteau et al., 2001; Guyot et al., 2006). Secondly, a distinction can be found in their fields of application. Companion modelling and role-playing games are mainly applied to land use (Castella & Verburg, 2007; Vieira Pak & Castillo Brieva, 2010), while participatory simulation is frequently applied to epidemics (Delaney et al., 2013; Kleczkowski et al., 2015). Lastly, participatory simulation is typically mentioned along with a validation, while companion modelling is rarely mentioned with a validation, with very few exceptions (Castella & Verburg, 2007). Interestingly, there seems to be no direct connection between papers comprising the use of the serious game category and those using RPGs (Figure 7). Serious game papers are typically focused on the use of games to educate and prepare individuals for making critical decisions in various fields, such as global food security, epidemiology, biodiversity conservation management, city development, and refugee aid (Anderson et al., 2017; Briot et al., 2017; Perez Estrada et al., 2017; Yang et al., 2020).

Research clusters of GAM research:

Further insight into the historical development of GAM research can be obtained by observing existing co-author networks of publications. Results from this section were gathered via an SNA performed on the sample gathered through the SLR (Szczepanska et al., 2022a). The SNA uncovered seven co-author clusters. However, the sample also included 26 single papers wherein the authors published only one study and had no connections to other publications. This finding suggests that researchers who use GAM are often from outside the clusters (as described in the following section) and produce isolated studies. Furthermore, no apparent links indicate a strong cooperation between the seven main clusters. This disconnectedness between publications may impact the overall coherence and progress of GAM research and highlights the need to promote cooperation and a shared methodology among researchers.

This section describes the seven most prominent clusters and highlights their distinctive traits. A video of how the clusters emerged over time from 2001 to 2020 can be found on GitHub[4].

[4] Link to the video: https://github.com/tmrmn/gam/

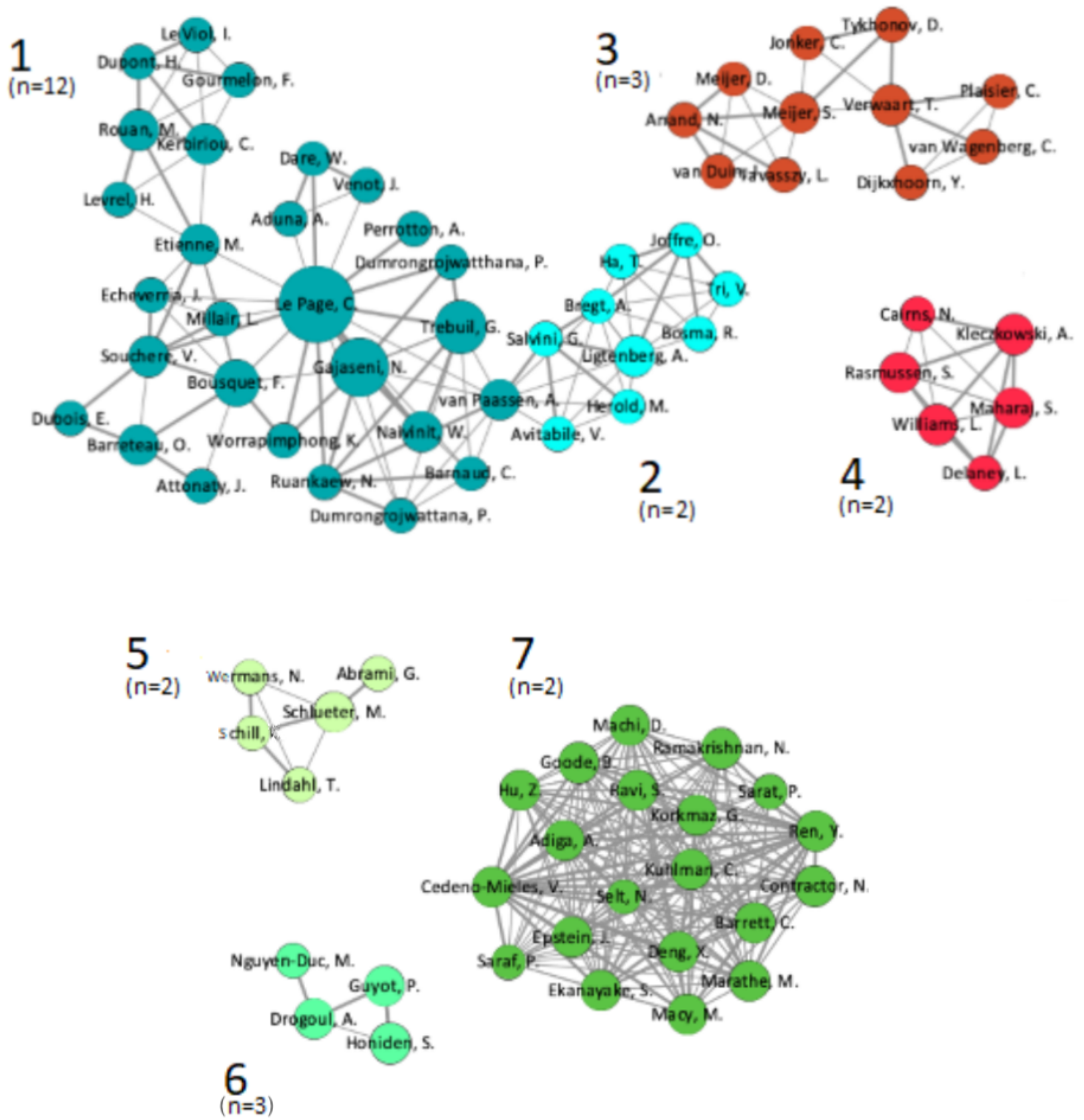


Figure 8 Seven Author Clusters with More Than Two Publications Regarding Games and Agent-Based Models. Created using the articles included in the SLR published in Szczepanska et al. (2022a). Author clusters are distinguished by colour; n indicates the total number of articles published by the respective cluster.

Co-author cluster 1 (Figure 8, 1) pioneered GAM research. They accounted for 21% of analysed publications (11 papers) and 16% of the researchers (28 out of 179 authors). Their research strategy comprised mainly small-scale, international collaborations between scholars from France and Southeast Asia (Thailand and Cambodia). The cluster includes prominent figures such as Oliver Barreteau, Francois Bousquet, and Christoph Le Page. It is closely related to the activities of The French Agricultural Research Centre for International

Development located in Montpellier. The work of the scholars from cluster 1 covers various application domains that are mostly related to nature resource management (e.g., agriculture, forestry, conservation, and water management).

Co-author cluster 2 (Figure 8, 2) is characterised by a strong representation of scholars from Wageningen University. The cluster is a product of collaborations between nine researchers who published two papers on participatory approaches in Vietnam. Wageningen University's role in bridging games with ABMs is even more significant as a collaboration between researchers from the university (Annemarie van Passen and Giulia Salvini) and bridges clusters 2 and 1.

Co-author cluster 3 (Figure 8, 3) is another cluster related to Wageningen University. The cluster comprises 11 researchers who wrote three articles regarding their experimentation with combinations of simulation games and ABMs. The cluster was first published in 2008 and is centred around the cooperation of a game researcher (Sebastiaan Meijer) and a researcher involved with modelling multi-agent systems (Tim Verwaart).

Co-author cluster 4 (Figure 8, 4) comprises a collaboration between six scholars from three Scottish universities: University of Strathclyde, University of Stirling, and University of the West of Scotland. The researchers co-authored two publications using virtual experiments to investigate human behaviour during an epidemic. Both papers merged the game and ABM components into a single application.

Co-author cluster 5 (Figure 8, 5) comprises five researchers (around Maja Schlüter) who published two articles to explore the potential of game and ABM combinations to explore and manage complex socio-ecological systems. They worked with stakeholders on organising the efforts of individuals and institutions for managing natural resources.

Co-author cluster 6 (Figure 8, 6) comprises four authors from France (Paul Guyot, Alexis Drogoul, and Minh Nguyen-Durand) and Japan (Shinichi Honiden) who concentrated on developing infrastructure for agent-based participatory simulations that allows human players to manipulate a computer simulation via a user interface.

Co-author cluster 7 (Figure 8, 7) emerged in 2018 as a collaboration of 19 scientists almost exclusively affiliated with the United States of America, except for Vanessa Cedeno-Mieles, who originates from Ecuador. The high clustering coefficient of 1 means that all the researchers co-authored both the published papers. The cooperation includes renowned agent-based modellers such as Joshua Epstein and Michael Macy and applies where ABM proceeds with a game setup.

4.2. Philosophical and Theoretical Foundations of GAM Research

The philosophical and theoretical foundations of GAM research discuss fundamental questions regarding the nature of reality, role of human interpretation, and concepts used to acquire knowledge. This study follows the conceptualisation proposed by Crotty (1998) and subsequently adapted by Creswell & Clark (2017) of four primary components used in designing and conducting research. According to this conceptualisation, the philosophical assumptions set the epistemological (the way of perceiving the world and making sense of it) groundwork for how researchers acquire knowledge. The philosophical assumptions shape the researcher's selection of a theoretical stance. The theoretical stance influences the methodology, including the research design steps. Lastly, the methodology controls the techniques used to collect, analyse, and interpret the data. In the following paragraphs, I first discuss the philosophical and theoretical foundations of GAM research and discuss how they relate to explanations and knowledge production.

4.2.1. Epistemology of GAM Research

GAM research is aimed at understanding or representing the laws governing reality in a systematic manner, and different philosophical perspectives offer various answers to this question. Three essential perspectives on this topic are realism, materialism, and idealism.

Realism proclaims the existence of an external reality that is separate from human beliefs. It argues that objective laws govern both the social and natural worlds (Sayer, 1992). Realism involves perceiving universal laws as applicable to all realms. In the context of GAM research, realism can influence researchers by emphasising the representation of real-world dynamics and interactions in their models. Realist researchers may aim to create simulations that accurately reflect the underlying mechanisms and processes of the system being studied, with the objective of observing a high level of correspondence between the model and the real world.

Idealism, in contrast, suggests that reality can only be known through human cognition and socially constructed meanings (Guyer & Horstmann, 2023). It highlights the subjective nature of interpretation and socially constructed meanings in shaping the social world. Within GAM research, an idealist perspective can cause researchers to focus on the role of human behaviour, beliefs, and social interactions in modelling complex social systems and explore how these subjective factors shape the overall dynamics of the system.

Materialism claims that reality is solely constituted by material features. This perspective posits that all facts, including those related to the human mind, are causally dependent on physical processes (Stoljar, 2023). It tends to focus on the physical aspects of the world and often aligns with scientific disciplines that rely on empirical observations and measurable phenomena. In GAM research, a materialist perspective can influence the selection and inclusion of variables and parameters in models. Materialist researchers may prioritise grounding their models in measurable and observable aspects of the system being studied as well as emphasising empirical data collection.

It is important to understand that the philosophical perspectives in GAM research are not necessarily opposed to each other. Researchers often merge aspects from multiple perspectives to different extents. The philosophical perspective selected can influence the research questions, model design, and interpretation of results in GAM research. Researchers may adopt a realist perspective to capture the external reality, an idealist perspective to emphasise subjective interpretation, or a materialist perspective to focus on sensors and empirical data. The choice of perspective depends on research goals, the complexity of the system being studied, and the disciplinary background and beliefs of the involved researchers. Differences in the research traditions and research subjects have a significant impact on the principal perspectives in a research field. This influences the way scientists ask questions about a research problem, what role they take on in relation to the research subject, and what knowledge they produce from answering the research questions.

4.2.1. Participatory Stance

In participatory research (Park, 1993), community-based participatory research (Israel et al., 2005), and participatory action research (McIntyre, 2007), the researched community is at the centre of the research process. GAM research builds upon the principles of participatory communication and modelling methods and extends them by integrating multi-level analysis and dynamic gameplay and simulation into the research process.

A significant difference between a participatory stance and conventional methodologies lies in the distribution of power throughout the research process (Cornwall & Jewkes, 1995). The participatory stance reflects the paradigm shift known as the communicative turn, which emerged in planning theory towards the end of the 20th century. This turn emphasised a transition from an expert-driven approach, wherein the researcher is expected to provide expert advice, to a collaborative approach that values the diverse expertise and contributions of stakeholders (Healey, 1992; Innes, 1995).

GAM research is tailored to facilitate knowledge exchange among experts, scientists, and laypersons. It uses games for different modes of communication to foster meaningful dialogue, encourage diverse perspectives, and promote the co-creation of knowledge. By adopting the participatory stance, GAM research becomes a platform for the community to engage with and shape the research outcomes actively. The research findings are not imposed on the community but co-developed instead, thus ensuring that they are meaningful and applicable to the community’s context. Through this approach, GAM research catalyses community empowerment, knowledge exchange, and social transformation.

GAM research cultivates an environment in which researchers and the researched community co-create "useful" knowledge that supports social and political change. Researchers work closely with community members to define research questions that align with their needs and priorities. By involving the community in this early stage, the research becomes more relevant and responsive to the community’s concerns and challenges.

Throughout the implementation of GAM, the participatory lens ensures ongoing engagement and dialogue with the community. Instead of researchers solely dictating the mechanics and model parameters, they collaborate with the community to ensure that the games and model mechanics accurately represent their experiences, real-world dynamics, and interactions. For this, researchers facilitate workshops wherein community members actively participate as players in games to create or refine agent behaviours. The community's input is essential in determining what scenarios are of interest, what variables are included, and how and which agent behaviours are modelled.

Furthermore, the participatory stance promotes transparency and open communication between researchers and the community. Regular feedback sessions allow community members to share their insights, challenge assumptions, and contribute expertise. This collaborative process allows for the co-production of knowledge as researchers and community members learn from each other and build a shared understanding of the issues.

4.2.2. Causation and Mechanism-based Explanations in GAM Research

The way a scientist asks a question about a research topic affects the answers they produce. As discussed by Antosz et al. (2022), these answers reflect the scientist's understanding of cause and effect and their preferred approaches to investigating causal relationships. This alignment is further influenced by factors such as background knowledge, dominant practices, and the formal language of causality in their research field.

In the physical sciences, a deductive-nomological worldview is prevalent. This perspective relies on deterministic formulas to describe causal relationships in the inorganic world (Hempel & Oppenheim, 1948). Explanations follow a deductive approach that is logically derived from premises that include general patterns observed in the world. One of these premises is a law of nature based on general patterns observed in the world.

However, social sciences often employ quantitative methods, such as experiments or survey questionnaires, to express social phenomena probabilistically using regression models (Russo, 2009). Regression analysis offers various theoretical approaches to causality. For example, Hempel (1965) proposes inductive-statistical explanations wherein the effect is likely to follow a cause. Salmon (1971) suggests a statistical relevance model wherein causes should have an impact on the occurrence of the effect. Mackie (Mackie, 1974) introduced the INUS model, which explores combinations of causes. In experimental and quasi-experimental research designs, counterfactual models of causal inference are commonly used. In counterfactual approaches, the causal effect is described as the difference in the effect when a cause is present to a situation wherein the cause is not present (Rubin, 1974; Holland, 1986; Lewis, 1986). Qualitative methods such as case studies, in-depth interviews, or focus group interviews use causal processes for investigating events that influence other events (Mohr, 1982; Salmon, 1984).

GAM research uses ABM to express causal models through mechanism-based explanations. In ABM, researchers focus on describing the underlying mechanisms or processes that drive (social) phenomena. ABMs are focused on describing the underlying mechanisms or processes that drive social phenomena. It is based on the idea of structural individualism, which states that individuals' properties, actions, and relationships can explain social facts. By combining games and agent-based models, GAM offers a flexible approach with various applications, incorporating diverse types of causation as elements of the mechanism, including agents, operations, and relationships. For example, the integration of games and ABMs allows researchers to explore probabilistic relationships. Researchers can leverage structural similarities between games and agent-based models and operate both the game interface and agent-based meta-model simultaneously. By incorporating observations from gameplay into the ABM, scientists can determine the probabilities for certain actions, calibrate the model, and collect data for validation purposes. Another method of using GAM research is to use the ABM to explore a wider parameter space (Bhattacharya et al., 2019; Cedeno-Mieles et al., 2020) by running different simulation scenarios with the game-calibrated ABM.

4.2.3. Complexity and GAM Research

This section presents an investigation of the concept of complexity and how complexity science reframes how systems that could only partially be understood by traditional scientific insights are researched as CASs by studying the patterns of relationships within them, how they are sustained, how they self-organise, and how system outcomes emerge (Zimmerman et al., 1998).

There are many definitions of complexity (Edmonds, 1999) and multiple approaches to researching complexity. Sciences have traditionally employed reductionism anchored in realist philosophy, which involves breaking down entities into smaller parts to obtain a better understanding (Westhorp, 2012). While this reductionistic framework has been beneficial in the past, it is inadequate for addressing the complexities of wicked problems (deMattos et al., 2012). Complexity allows for contextual and local generalisations, while rejecting universal generalisations (Morcol, 2001). The idea of complexity science is that a system cannot be adequately explained by studying its isolated components; rather, it must be understood holistically as a complex system by examining its inherent interplay and interactions. Complexity science offers an expanded perspective as it involves examining the individual parts that contribute to the whole and understanding how each part of a system interacts with all the others, which results in the emergence of a new entity. This comprehensive approach enables a more thorough and holistic understanding of complex systems (Turner & Baker, 2019). Complexity science encompasses various disciplines (including ABM) and theories that describe and are focused on the study of complex systems (Mitchell, 2009; Castellani, 2014). What connects them is their view of complexity as a tool for analysing and making sense of the existing world while acknowledging that complex interactions may obscure reality. Over the past 25 years, the study of social complexity has led to the development of various methods that assist scientists in analysing complexity. These innovations have been recognised as a paradigm shift, which is known as the complexity turn (Urry, 2005).

ABM plays a vital role in GAM research, enabling researchers to simulate and analyse the behaviour of complex systems. In agent-based models, entities within a system are represented as autonomous agents with their own decision-making processes. The ABM component allows researchers to observe how the actions and interactions of these agents result in emergent outcomes and patterns within the system. ABM is aligned with the core principles of CAS, which emphasise the interconnectedness of system components, emergence of new behaviours, and adaptability of systems. Adaptability in this context means that the system can change by learning from previous experiences (Abbott & Hadžikadić, 2017). The CAS tends to self-organise, which results in new emergent behaviours that cannot be observed by studying the individual parts alone (Edmonds & Meyer, 2017; Miller & Page, 2007).

A CAS does not exhibit a linear relationship between its components and processes, which makes a precise long-term prediction of its system states practically impossible (Borit, 2013). Consequently, a one-size-fits-all approach for predicting and controlling a CAS is ineffective (Sargut & McGrath, 2011). Furthermore, these emergent behaviours are not controlled by any single part of the system (Mitchell, 2009). Instead, these systems require a flexible, context-specific, and multi-level approach to ABM and, as such, to GAM research, analysis, and management, which results in contextual and local generalisations.

To illustrate the concept of CAS, let us consider the example of a fish swarm. Hundreds, or even thousands, of individual fish, swim together in a coordinated manner through the ocean. The swarm moves as one entity, sweeping back and forth and splitting into smaller squads to navigate obstacles before reuniting in a formation. Although the behaviour of the fish swarm is complex and sometimes unpredictable, it demonstrates a system composed of interacting individuals. The swarm's complexity arises from the large number of individuals and their collective movements. Furthermore, the swarm exhibits adaptability as it adjusts to its environment and influences. While the fish swarm does not directly represent human realities, it serves as an analogy for social systems, emphasising that systematic interactions between individuals can result in surprising global outcomes. Schelling's model of suburban segregation (Schelling, 1969, 1971) provides an excellent example of this and demonstrates how individual preferences can give rise to broader societal patterns, such as a broadly segregated map, at the macro scale.

To thoroughly represent the emergence of a CAS, a model must encompass its main properties. It is emphasised that not only should the model itself be a CAS, but the process of creating the model should also be complex and evolutionary. It is essential to start with a simple method for generating simple models and gradually evolve towards a complex method for generating complex models. This is where GAM—because it incorporates ABM—proves to be a powerful tool. As Epstein (1999) stated, "If you didn't grow it, you didn't explain its emergence". ABM is the only tool that allows for this, as it captures the fundamental social structures and group behaviours that emerge from the interactions of agents operating in artificial environments under rules that place limited bounds on each agent's information and computational capacity (Epstein & Axtell, 1996).

4.3. Critical Foundations

The critical foundations of GAM research encompass ethical considerations to promote integrity and responsibility in science. Traditionally, discussions on research ethics have been primarily focused on research misconduct. However, recently, the scope of these discussions has expanded to include integrity and responsible research, thus emphasising the importance of ethics as an integral component and safeguard for good research practices (Anzola et al., 2022).

Both the games and ABM research communities reflect critically on ethical considerations related to their practices. As games and ABM are integral parts of GAM research, it is crucial to draw inspiration from these discussions. In ABM, ethical challenges arise from computer modelling and simulation practices, disciplinary dynamics, and technological aspects (Anzola et al., 2022; Shults et al., 2018). Similarly, critical game studies explore technological, social, cultural, and political–economic challenges within the interdisciplinary study of games. A recent article by Pötzsch et al. (2023) presents a framework for critically evaluating video games based on ontological game models. The framework is relevant in the context of GAM research as it takes into consideration the sign system, rules and mechanics, materiality, and players.

To promote a collective ethical discussion, the critical foundations of GAM research borrow ideas from both research domains (games and ABM). They distil a catalogue of reflective exercises divided into three parts: ethics of research, ethics of technology, and social ethics.

(I) Ethics of research: While considerations regarding research ethics are not exclusive to the GAM research field, it is crucial to enhance the ethical integrity of science in general and contribute to knowledge advancement. GAM research should avoid perpetuating discriminatory narratives or biases. Foucault (1990) emphasises the importance of critical thinking in exploring discourse that reproduces power relations. Therefore, it is crucial to acknowledge the influence of socially constructed power relations on our thoughts and existing social practices in everyday life, which reinforce dominant values and biases, including those in science. Through critical reflection on research practices, researchers can uncover pre-existing assumptions that contribute to power imbalances and challenge them (Lather, 1991). The critical foundations of GAM research not only involve reflective praxis but also serve as a call to action. Researchers can use a code of conduct to shape their everyday research practices, and examples of such codes that emphasise professionalism and ethics for researchers working with simulation-based methods have been provided by Ören et al. (2002) and Anzola et al. (2022).

(II) Ethics of technology: GAM uses digital modelling and simulation tools to collect and produce possibly sensitive outputs. Data privacy (including obtaining consent and protecting participants' privacy) is crucial in GAM research, especially when collecting data on behaviours exhibited during gameplay or acquiring inside knowledge from stakeholders on specific real-life problems. The implementation of privacy protection measures promotes the ethical use and confidentiality of personal data (Bowser et al., 2017). Communicating the risks and benefits of data collection empowers participants to make informed decisions about their involvement.

GAM research studies, especially those aimed at providing policy advice or promoting community learning, can have significant real-world implications. Researchers need to consider the potential consequences of their findings, including identifying "problematic" social dynamics in decision-making processes and policy development. By assessing potential risks and unintended consequences associated with the application of models, researchers can actively work to mitigate any negative effects. This also includes addressing unintentional biases in algorithms or game mechanics caused by the selected population to inform algorithms and parameterisation (Keyes et al., 2017).

Reflecting on the mechanics of GAM research applications involves considering the options players or agents have when interacting with the environment and understanding the perspectives that influenced researchers' decisions to implement specific mechanics. Sharing the model code and GAM research descriptions and making them available for review is also considered good practice (Section 5.2.1).

(III) Social ethics: Ensuring access to information and GAM research management is crucial for organisations and communities involved. Engaging with researchers and stakeholders from diverse backgrounds, particularly marginalised communities, aids in avoiding biases and ensures that research takes into consideration a wide range of perspectives and localised knowledge. While GAM research is aimed at attracting people beyond academia, it is essential to reflect on the inclusion and possibilities for engagement of participants, considering that structural inequalities can result in the exclusion of individuals from low-income and minority ethnic backgrounds (Dawson, 2018).

When considering the player's role, evaluating player selection and how players engage with GAM is crucial. GAM research should explore how games can counteract misogyny and other harmful cultural aspects and should prioritise inclusivity (Humphreys, 2019). Instead of assuming a position of a powerful expert assigning players a passive role, GAM research should provide opportunities for players and participants to influence game mechanics and narratives. The inclusion of diverse perspectives promotes fairness and helps prevent the preservation of existing inequalities that contribute to oppressive structures. Researchers must understand the ethical challenges specific to their research fields and the ethical issues that can arise from disciplinary dynamics. The accessibility of selected approaches is also important, and researchers should consider the technological, economic, and expertise requirements to conduct the study. Researchers must actively address potential discrimination by critically examining and mitigating biases present in data, model assumptions, player participation, and the interpretation of results. By considering these factors, researchers can promote fairness and inclusivity within GAM research.

(IV) Transparency in GAM research is crucial. Researchers should openly discuss the methodology, data sources, assumptions, and limitations of their models. Transparent reporting allows for scrutiny from the research community for identifying potential biases and gaps. Clear documentation supports the reproducibility of game research in different contexts and allows others to assess and validate GAM studies, ultimately facilitating advancements in the field. This thesis presents two frameworks that support researchers in ensuring clarity and transparency in their GAM research (Section 5.2).

5. Designing GAM Research

Research designs are essential in directing methodological decisions and establishing the sequence for collecting, analysing, and interpreting data for research studies. In the context of GAM research, research designs are particularly important owing to the unique challenges of braiding-game and ABM components.

This section aims to provide readers with guidelines for designing and conducting GAM research studies. It discusses sequencing game and ABM elements, matching research designs to research purposes, and the importance of clarity and transparency in GAM research. Furthermore, readers are introduced to six prototypical GAM research designs, each with its own purposes, applications, and procedures for integrating game and agent-based model elements.

5.1. Guidelines for Designing a GAM Research Study

The design of research studies can be a challenging process. It becomes even more challenging when incorporating the two GAM research components into a research design for addressing complex problems. To make this process less daunting, this section outlines two key considerations for researchers when designing a GAM research study. It is important to note that these guidelines are not intended as set-in-stone instructions but rather as a starting point to expand a shared knowledge base about how to design and conduct GAM research and to guide methodological discussions.

5.1.1. Sequencing, Correspondence, and Target Systems in GAM Research Designs

When designing a research study involving a game and an agent-based model component, researchers can draw inspiration from ideas discussed in the context of mixed-method procedures. One crucial aspect of this is sequencing, which involves determining the timing and order in which different research components are executed (Morgan, 2017). In mixed-method research, sequencing typically refers to the order of qualitative and quantitative data collection (Creswell & Creswell, 2017). In the context of GAM research, *sequencing* relates to the arrangement of game and ABM components.

The two main methods of sequencing are (1) sequential arrangement and (2) simultaneous arrangement. In a sequential arrangement, the ABM and game components are conducted in separate phases. The ABM can be conducted before the game or vice versa. It is also possible to arrange these sequences in iterative loops, wherein the game and ABM components are alternatingly executed. In a simultaneous arrangement, the ABM and game are arranged simultaneously. In some cases, both components are merged into a single application, thus blurring the boundaries between the game and ABM.

The game and ABM can correspond to each other in different ways, which provides researchers with the flexibility to arrange the components of GAMs in various configurations (Szczepanska et al., 2022a). *Correspondence* refers to how the game and agent-based model interact to address a research problem, the nature of their connection, and how they influence each other's design. To examine the correspondence, researchers can ask some of the following questions:

- Are the sequences of the game and ABM independent from each other, or do the results of one sequence inform specific aspects of the subsequent sequence?
- Do outputs of the ABM influence the processes and scheduling of the game, or is the ABM influenced by inputs from the game?
- Are the conceptual models of the game and ABM identical, or do they have elements that work differently? If they are different, how and why are they different?

When thinking about the *target system,* researchers consider whether the model and game represent the same real-world system or if they relate to different but connected or disconnected systems. The target system describes aspects of the real-world system that are studied to gain knowledge regarding the phenomenon under investigation (Elliott-Graves, 2020).

Notation system for GAM research designs: A notation system is necessary to communicate and understand the sequence and target system within a research design. In mixed methods research, we can find established notation systems that have been used and improved over the past 30 years (Cresswell & Clark, 2017). I suggest the use of the following adapted notation system for describing GAM research designs:

- Arrow "→": This indicates methods that occur in a sequence. A struck-through arrow "↛" indicates that the game and ABM do not describe the same target system.
- Plus "+": This indicates methods that occur at the same time.
- Equal "=": This indicates that the game and agent-based model elements are fully merged.
- Parenthesis "( )": This indicates that a sequence is embedded in a larger design.
- Double arrows "→←": This indicates methods that are implemented recursively.

Example notations: The "ABM → Game" notation indicates a sequential design in which the researcher begins with the ABM, and the game follows. The game and ABM processes of a GAM research design can be considered as building blocks that can be arranged in repeated loops (Game →← ABM), e.g., to feed back the results from the ABM phase to the participants. In a simultaneous GAM design (game + ABM), the game and ABM processes occur simultaneously (combined into a single sequence). The fully merged game and ABM approaches (game = ABM) allow the researcher to collect data while the player acts within the simulation.

5.1.2. Considerations When Matching a Research Design to a Research Problem

GAM research has been widely employed to address various research problems, and while research designs serve specific purposes and possess unique strengths, they also share many similarities. When matching a research design to a specific research problem, it is crucial to consider whether GAM research is appropriate for addressing the research question. Therefore, researchers need to have a clear understanding of the research topic, questions, and purpose of their study. While this seems rather obvious, many published GAM studies do not clearly communicate their research questions and the reason why they used a specific research design. Section 3.2 has already presented a discussion of the types of research questions that GAM research is particularly suitable for and has highlighted their effectiveness in addressing wicked problems embedded in complex systems that require the use of diverse research tools and perspectives. After researchers clarify the research topic, questions, and purpose, they can consult the prototypical GAM research design (Section 5.3).

In the context of designing a GAM research study, it is crucial to determine the specific contributions of the game and ABM components, as well as their *sequence*, *correspondence*, and *target system*.

Researchers need to consider the unique *contributions* and expected outcomes of both the game and ABM phases when addressing the research problem. For example, a game contributes in various ways to a GAM design, such as simulating real-world decision-making processes in a game setup, engaging participants to explore micro-interactions, or facilitating the exploration of complex system dynamics. Researchers should clearly articulate why incorporating a game is essential for their research and how it aligns with their research objectives. The ABM component allows researchers to model the behaviour and interactions of individual agents within a system. Its contribution could be the modelling of emergent phenomena, simulating different development scenarios or the impacts of interventions, or analysing the effects of individual mechanics on overall system behaviour. Researchers should identify the specific sub-goals and research questions that the ABM component are aimed at addressing.

Researchers should clarify the *sequence* of the game and ABM components. The choice of sequence (sequential or simultaneous) can impact data collection and how data flows between both components. The outcomes of the game phase could inform the parameterisation of the ABM, or the ABM results could provide feedback for modifying the rules or mechanics of the game. For example, this can be achieved by using a game to explore a topic along with players. An ABM can then be used to perform simulations that scale up findings from and observations of the gaming process. Alternatively, researchers can start with the ABM, and the game can follow to help explain the results obtained from the ABM with data collected during the game. It is also possible to use the game to calibrate, validate, or inform the agent-based model. In a simultaneous design, the game and ABM components are used simultaneously. This arrangement is advantageous when the researcher works on a well-defined research question and aims to gather specific data from the players or asks stakeholders for input on explicit aspects of a conceptual model. Specifying the sequence ensures a cohesive integration of the game and ABM components and clarifies how the game and the ABM correspond with one another. This also includes specifying what types of data (qualitative or quantitative) are collected and how the different data types are intertwined.

Researchers should be explicit about how a game and an ABM represent the *target system*. For example, the game and ABM may both represent different aspects of the same real-world system, providing complementary insights into its dynamics and behaviour. For example, the game may collect insights on decision-making among stakeholders, while the ABM represents the socio-ecological interactions within the system. Alternatively, the game and ABM may represent different but connected system elements. In this case, they may serve to explore different aspects related to the broader research problem.

Once these aspects have been carefully considered, it is crucial to describe the research design in a clear and explicit manner. By being transparent about the research question, purpose, and overall design, in addition to the use of notation systems, diagrams, or flowcharts, researchers can promote transparency and reproducibility in the field. The reporting of specific procedures used in executing the research design, such as data collection and analysis methods, would enable other researchers to replicate the study and build upon its findings. Examples of six prototypical GAM research design types (RDTs) are presented in section 5.3.

5.2. Ensuring Clarity and Transparency

Ensuring clear and transparent reporting of the research design is crucial for advancing the field of GAM research. Such reporting not only enhances the credibility of publications but also facilitates reproducibility. In the case of GAM research, the use of clear definitions supports cooperation in transdisciplinary settings involving scientists, experts, and laypeople from diverse backgrounds. Therefore, two frameworks are introduced to support practitioners in systematically reporting their contributions and producing accessible results that transcend subject boundaries. These frameworks, namely, the GAM DS and the GAM RF, serve as initial proposals that researchers can adapt and extend to meet their specific needs.

The GAM DS (Section 5.2.1) is designed to assist researchers in systematically documenting their GAM study. This scheme consists of a set of standardised categories for documenting the design and implementation of GAM studies. Using this scheme, researchers can provide a structured account of their research process, thus ensuring that key aspects of the study are clearly documented, such as the conceptualisation of the game and ABM elements, data collection methods, model calibration procedures, and evaluation criteria used.

The GAM RF (Section 5.2.2) encourages researchers to reflect on their experiences and insights gained from conducting a GAM study. This framework comprises a series of questions that prompt researchers to think critically about different aspects of their study. For example, researchers may reflect on the challenges encountered during the integration of the game and ABM elements, the effectiveness of the chosen modelling techniques, or the engagement and feedback received from participants. By engaging in this reflective process, researchers can identify areas for improvement, lessons learned, and potential future research directions.

Both frameworks can inform each other. As researchers engage in documentation, they may uncover areas wherein further reflection is required. Similarly, through reflection, researchers can identify gaps in documentation that need to be addressed. This back-and-forth process ensures that reporting and improvement are intertwined. It is important to note that both frameworks are considered a starting point, and researchers are encouraged to adapt and extend them as necessary to suit their specific requirements and research context. By embracing these frameworks and incorporating them into their reporting practices, researchers can contribute to the advancement of GAM research by providing clear and transparent documentation of their work and reflecting on their experiences to identify areas for improvement and further exploration.

5.2.1. GAM Documentation Scheme

The GAM DS proposed by Szczepanska et al. (2022a) serves as a tool for structuring and reporting GAM research studies (Table 2). Its primary objective is to provide researchers and practitioners with a systematic approach for documenting GAM research studies. The protocol was developed because existing publications in GAM research most often lack a comprehensive description of the study elements. Using the GAM DS, practitioners can effectively structure their studies, enhance the replicability of their research, and guide the design of future studies by offering a transparent framework that allows for easier identification of aspects that can be improved. Moreover, the scheme promotes collaboration between ABM practitioners and the games community, thus facilitating the consolidation of the GAM field and advancing methodological debates.

Table 2 Games and Agent-based Models (GAM) Documentation Scheme (Szczepanska et al. 2022a; with modifications). Explanations of how to fill in the framework are provided in square parentheses.

A) General aspects	1. Purpose of the study. [open ended] 2. Research questions of the study. [open ended] 3. Application field. [open ended] 4. Type of GAM research design. [1. Game --> ABM, 2. Game -/-> ABM, 3. ABM --> Game, 4. ABM -/-> Game, 5. Game + ABM, 6.ABM = Game] 5. Additional comments. [open ended]
B) GAM	1. Purpose of using the GAM methodology. [open ended] 2. GAM design (e.g., sequences, phases, procedures, iterations, information flow) [open ended] 3. How the game and ABM are linked (e.g., specific information from gameplay that was used to validate the ABM, how was the gameplay data used to inform ABM rules, how are ABM simulations used in the game). [open ended] 4. Limitations of the specific GAM implementation. [open ended] 5. Contributions of the use of GAM to answering the research questions of the study. [open ended] 6. Advice for others. [open ended] 7. Additional comments. [open ended]
C) Game	1. Target system. [open ended] 2. Type of game. [commercial off-the-shelf; built for purpose, but not for this study; built for purpose and for this study]. 3. Game type. [analogue; computer-based; mixed] 4. Game category: a. Dice and Luck: dice games, start-goal-games, search and catch games b. Layout games: letter layout games, lottery games, figure layout games, picture layout games c. Thinking games: strategic games, tactical games, combination games, memory games, solitary games d. Quiz/Communication games: question-and-answer games, quiz games, fortune-telling games, creativity games e. RPGs and simulations: economy games, criminal games, adventure games, conflict games f. Dexterity games: dexterity games, action games, reaction games, sport games g. Other: _______________. 5. Who the players are (e.g., stakeholders, students, fellow researchers, general public). [open ended] 6. How the players were selected. [open ended] 7. Game objective. [open ended] 8. Core game mechanics. [open ended] 9. Data collected from gameplay. [open ended] 10. How is the data collected from gameplay (e.g., observation, tracking etc.). [open ended] 11. If and how debriefing was performed (If debriefing was not performed, provide a reason for that decision). [open ended]] 12. Data collected after the gameplay. [open ended] 13. How is the data collected after the gameplay (e.g., questionnaire, interview, focus group). [open ended]. 14. What the ABM adds that would not be known otherwise. [open ended] 15. Additional comments. [open ended]
D) ABM	1. Target system. [open ended] 2. Link to filled in documentation/reporting protocol/scheme: _______________ 3. What the ABM adds that would not be known otherwise. [open ended] 4. Additional comments. [open ended].

Frameworks are a vivid topic in discussions on rigour and transparency. In the ABM domain, multiple frameworks in the form of documentation guidelines, standards, and protocols have been introduced. The development of the GAM DS was influenced by various existing frameworks, such as MR POTATOHEAD (Parker et al., 2008); Dahlem ABM Documentation Guidelines (Wolf et al., 2013); Delineate, Structure, and Gather (Altaweel et al., 2010); Engineering Agent Based Social Simulation (Siebers & Klügl-Frohnmeyer, 2017); and the Rigour and Transparency (RAT) reporting standard (Achter et al., 2022). Of particular significance is the Overview, Design Concepts, and Details (ODD) protocol (Grimm et al. 2006, 2010, 2020), which has become a standard in the ABM field. While the documentation frameworks in the games research domain are less developed, one notable framework is the Gameworld Design and Analysis for Socio-Ecological Systems (GASS) framework (Weines & Borit, 2022).

Drawing inspiration from these frameworks, the GAM DS clarifies the study's purpose and research questions, highlights research design choices, and elucidates how the game and ABM combination contribute to answering these research questions. It thus addresses two main categories: (1) formal considerations of the conceptual design of the GAM research approach of the respective study, encompassing contributions to existing knowledge, the rationale for performing it, and the specific problem it aims to address; and (2) general considerations related to the organisation of work, structure, development tools employed, and outcomes. As in the case of the ODD protocol, the GAM DS is expected to evolve and mature as researchers become more experienced with its application.

GAM DS consists of four categories: general aspects of the study, the GAM research approach itself, the game used, and the agent-based model. Each category features specific questions regarding the purpose, design, limitations, and data collection methods, as well as the contribution of the GAM research approach to answering the research questions. While the ABM category within the GAM DS is comparatively shorter, it is worth noting that the ABM field already has well-established documentation and reporting protocols that can complement the GAM DS. The ODD protocol and the RAT reporting scheme offer comprehensive approaches to documenting ABM aspects. For thorough research documentation, researchers should merge the GAM DS with the current ABM documentation and reporting protocols. This integration would provide a more holistic view of the study by capturing the unique aspects of GAM research and established practices in the ABM field.

The framework can be filled in before, during, or after the design process. The framework has four parts, (A) general aspects, (B) GAM, (C) game, and (D) the ABM, and it includes explanations regarding how to fill it in. The questions in this framework are focused on two main aspects: descriptions of the design choices and explanations of why the choices are made. A demonstration of the framework is presented in Section 6.

5.2.2. GAM Reflection Framework

The GAM RF published in (Szczepanska et al., 2022b) is designed to support researchers in tackling the disciplinary boundaries of interdisciplinary and transdisciplinary teams. The GAM RF is a valuable tool for anyone involved in designing and conducting GAM research, as it promotes reflection and communication throughout the design process, enhances interdisciplinary collaboration, and is ultimately assumed to result in more effective and efficient research outcomes.

Reflection plays a crucial role during the design process, given that a GAM study often depends on the expertise and perspectives of various research fields. Collaboration between scientists, experts, and laypersons from different backgrounds with sometimes contrasting paradigms, e.g., games, game design, participatory research, ABM and simulation, and quantitative and qualitative analysis, can result in fruitful discussions and innovative solutions. However, the contrasting paradigms and methodologies may create misunderstandings. Each discipline has its own jargon, assumptions, and approaches to problems, which can result in communication gaps and difficulty in finding common ground. Moreover, conflicts may arise as various disciplines prioritise different aspects of the research process and rely on practices that are common in a field as granted. It is essential to enable domain experts to access the results of their in-GAM studies in a clear and transparent manner to overcome cross-subject boundaries and consequently allow the creation of new knowledge, theories, and methods to solve a specific research goal. The GAM RF was developed to transform the concrete experiences (tacit knowledge) of practitioners into abstract concepts by facilitating structured reflections on what is combined in a GAM study in addition to how and why.

Table 3 GAM Reflection Framework (Szczepanska et al. 2022b)

Part 1: Formal reflections	
WHAT contributes to GAM?	
What disciplines and knowledge bodies were involved and integrated?	
In the ABM	
In the Game	
HOW was GAM performed?	
Which resources were used? Explain why these were used.	
Empirical (datasets and sources)	
Methodological (methods)	
Theoretical (theories)	
Technical (tools)	
WHY GAM is used?	
What new knowledge is produced by the GAM design? What problem does it aim to solve?	
Epistemological (to produce new understanding and knowledge)	
Instrumental (to solve a problem or a societal challenge)	
Part 2: General reflections	
Team (organisation, communication, etc.)	
Game engines or platforms (pros and cons, challenges, etc.)	
Transparency and rigour (measures adopted, etc.)	
Stakeholders (interaction, etc.)	
Outputs/outcomes (what was produced, how it was received, etc.)	

The GAM RF was inspired by findings from education research that hint that a well-structured intentional reflection during activities reinforces cognitive and affective development (Cavilla, 2017). The protocol for assessing the interdisciplinarity of models (Huutoniemi et al., 2010) and the framework to guide and facilitate interdisciplinary social-ecological system research in practice (Weber et al., 2019) were the main sources of inspiration for developing the GAM RF. Findings from the above framework were synthesised and tailored to match the needs of GAM practitioners. The GAM RF is aimed at promoting reflection and communication throughout the design process, enhancing interdisciplinary collaboration, and realising more effective and efficient research outcomes. To achieve these aims, it caters to three concrete demands: (I) reflections on practices, (2) reflections on the interdisciplinarity of the GAM study, and (3) reflections on the suitability of specific GAM design elements for addressing a particular research problem. The document is divided into two parts: formal reflections and general reflections. The questions cover formal and general reflections, including the disciplines involved, resources used, team organisation, and stakeholder interaction. The framework helps to evaluate the effectiveness of a research approach in producing new knowledge and achieving its intended goals.

Part 1: Formal reflection. The first part guides reflections on the interdisciplinarity of the endeavour, including questions on the disciplinary backgrounds and knowledge bodies involved in the GAM research design. Furthermore, it prompts reflection on the resources utilised, including empirical data sources, methods, theories, and technical tools. This section also prompts the consideration of the epistemological and instrumental aims of the GAM approach, specifically what new knowledge was produced and what problem it is aimed at solving. **Part 2: General reflections.** The second part is structured around the general process of designing and conducting GAM research in a transdisciplinary manner.

GAM practitioners can use the GAM RF before, during, and/or after the GAM study to reflect on their research and optimise their practices, thus increasing the rigour and transparency of their work. ABM modellers and game designers can use it to structure collaborative work in interdisciplinary teams or assess whether a GAM research design is suitable for addressing a particular research question, while research coordinators can use the GAM RF as a blueprint for planning research tasks and requirements. A demonstration of the framework is provided in Section 6.

5.3. Prototypical GAM Research Design Types

This section provides an overview of six prototypical research designs of GAM identified by Szczepanska et al. (2022a). A GAM RDT serves as a blueprint for researchers when developing the research design of their own studies. Table 3 presents a comprehensive summary of the GAM RDT and highlights the game and ABM sequence, target system, correspondence between the game and ABM, and the purpose. Researchers can refer to this table to obtain a better understanding of the RDTs and select the most suitable one for their specific study. The use of the prototypical designs along with the guidelines for designing a GAM study (Section 5.1) and the conceptual frameworks (Section 5.2) would aid researchers in designing, implementing, and describing their GAM study rigorously and transparently.

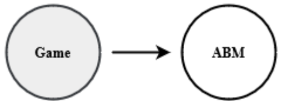
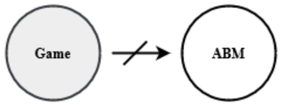
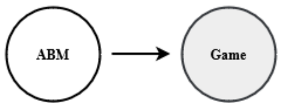
The following sub-sections offer a practical description of each GAM RDT, providing insights into their purpose, criteria for selection, as well as their strengths and challenges. The application domains of RDTs per article are listed in Table 4. Each subsection concludes with examples of publications applied to the respective research type. These examples have been selected to demonstrate a wide range of application domains (see Appendix E: Prisma Diagram Game and ABM SLR (2021-2023)).[5]

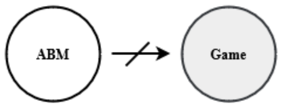
Table 4 Overview of the Application Domains of the Articles by GAM Research Design Type

	Type 1	**Type 2**	**Type 3**	**Type 4**	**Type 5**	**Type 6**
Natural resource management	9		5	4	5	4
Group dynamics		2		3		2
Public health						3
City logistics			2		1	
Attitude-behaviour relation		1		1		
Natural risk management						2
ABM methodology/ validation			1			
Air traffic management						1
Business management						1
Construction management						1
Organisational management				1		
Emission trading						1
Humanitarian logistics						1
Security						1
Total	**9**	**3**	**8**	**9**	**6**	**17**

[5] Appendix 9.2 is part of the SLR conducted for my second publication Szczepanska et al. (2022a).

Table 5 Description of Six Prototypical GAM Research Design Types (Szczepanska et al., 2022a; with modifications)

GAM RDT Notation	Game/ABM Sequence	Target System	Game/ABM Correspondence	Purpose and Applications
Type 1 Game → ABM 	From game to ABM	Identical	The ABM design is influenced by the processes and scheduling of the game; both use the same concept model.	Suitable for promoting communication, mutual understanding, or learning among stakeholders and scientists. Aims to understand a group of stakeholders at the collective level. Most used for the following: • stakeholder involvement • citizen science
Type 2 Game ↛ ABM 	From game to ABM	Different	The ABM is independent of the game processes and scheduling: results from the ABM could lead to game adaptation.	Aimed at understanding or analysing decisions or interactions in a game through the application of ABM. Most used for the following: • improve game performance • improve player experience
Type 3 ABM → Game 	From ABM to game	Identical	The game design is influenced by the processes and scheduling of the game; both may use the same concept model.	Suitable for gathering additional knowledge. Aimed at verifying, validating, or calibrating the simulation. Most used for the following: • community-based science • stakeholder involvement

<table>
<tr><th>GAM RDT Notation</th><th>Game/ABM Sequence</th><th>Target System</th><th>Game/ABM Correspondence</th><th>Purpose and Applications</th></tr>
<tr><td>Type 4
ABM ↛ Game

</td><td>From ABM
to game</td><td>Different</td><td>The game is independent of game processes and scheduling: results from the game may lead to ABM adaptations.</td><td>Aimed at using games to investigate questions revealed by the construction and analysis of the ABM that were not obvious when making the ABM. Aimed at discovering knowledge/ answers posed by the ABM and its analysis. Most used for the following:
• research human behaviour
• business games</td></tr>
<tr><td>Type 5
ABM + Game

</td><td>Simultaneous</td><td>Identical or different</td><td>ABM is part of the game.</td><td>The ABM implements a (sub-) component of the game. Most used for the following:
• stakeholder involvement</td></tr>
<tr><td>Type 6
ABM = Game

</td><td>Simultaneous</td><td>Identical</td><td>The ABM and game are intertwined in one application: agent-based game.</td><td>The ABM provides the infrastructure for game interaction and play. Most used for the following:
• stakeholder involvement
• business games/simulation games</td></tr>
</table>

5.3.1. GAM Research Design Type 1: Game → ABM

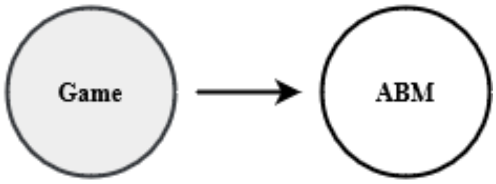


Figure 9 Prototypical Schemata of GAM Research Design Type 1

Sequence, target system, and correspondence: The sequence of GAM RDT 1 (Game → ABM) begins with a game that informs a subsequent ABM (Figure 9). This GAM RDT employs the game as a means of supporting the design process of the ABM. In such a setting, the game, often in the form of an RPG, is employed as a facilitation tool for gathering, discussing, and incorporating stakeholder knowledge into the research process. The game setting allows stakeholders to play-test and debate system elements to determine which parts and properties are relevant for the investigation. GAM RDT 1 is often linked to companion modelling (Étienne, 2014) and participatory modelling and simulation (Castella et al., 2005). The ABM is developed in alignment with the target system of the Game. The ABM component facilitates communication and discussion of development scenarios. In GAM RDT 1, the game and ABM correspond via an interim step of translating observations made during the game into the agent-based model mechanics (e.g., participants are playing a specific situation in an RPG, behaviours they exhibit are collected, and the modeller implements these behaviours into agents). Throughout the research process, researchers may repeat the game-to-ABM sequence to incorporate additional data sources or evaluate the findings.

Purpose: *GAM RDT 1* is aimed at gaining in-depth knowledge to improve the understanding of a particular phenomenon. It facilitates participatory research in co-constructing or improving representations of real-world systems.

When to choose it: *GAM RDT 1* is appropriate when researchers want to access local or expert knowledge during the research process. For instance, to support decision-making processes by investigating a problem and developing strategies to tackle it along with members from the affected communities.

Strengths and challenges: The strength of GAM RDT 1 is its straightforward process of using a game as a tool for data collection and facilitation. The involvement of stakeholders in gameplay can enhance their engagement, particularly those directly impacted by the researched processes. The insights gained during the game can be further explored during debriefing sessions, thus allowing both researchers and participants to deepen their understanding of a research problem. The possibility of iteratively repeating the game-to-ABM sequence allows for continuous refinement of the target system.

The creation of a game and an agent-based model, as well as facilitating workshops can be a time-consuming process. In this context, a benefit of RPGs is the limited time and effort requirements for creating them. RPGs allow for greater flexibility in their execution, as they can be developed and implemented relatively ad-hoc without the need for extensive rule-setting, mechanics, and balancing stages. However, challenges may arise in the case of data analysis and validation of findings, given the subjective and potentially fragmented nature of the gathered expertise. Therefore, careful attention should be focused on the selection of players who represent relevant stakeholders and possess the knowledge necessary to contribute meaningfully to the research.

Table 6 Examples of Publications that use GAM Research Design Type 1

Publication	**Domain**	**Purpose**
D'Aquino & Bah (2014)	Natural resource management, land use policies	Stakeholder involvement, self-design of innovative environmental policies
C. Le Page et al. (2014)	Natural resource management, land/water use, and labour migration	Stakeholder involvement, understanding interactions between water-resource and water-use dynamics
Salvini et al. (2016)	Natural resource management, agriculture, land use strategies	Stakeholder involvement, assessment of the impact of land management policies and interventions on land-based mitigation and adaptation goals

5.3.2. GAM Research Design Type 2: Game ↛ ABM

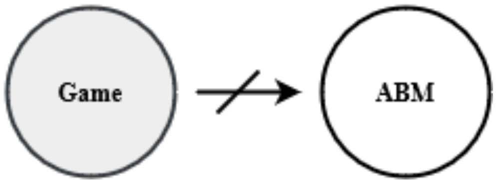


Figure 10 Prototypical Schemata of GAM Research Design Type 2

Sequence, target system, and correspondence: The sequence of GAM RDT 2 (Game ↛ ABM) begins with a game that informs a subsequent ABM (Figure 10). In GAM RDT 2, a game is used to collect game (-play) data, and in the subsequent ABM, the collected data is explored and analysed. Although GAM RDT 2 follows the same sequence as GAM RDT 1, it differs in that the game and ABM do not represent the same target systems. The correspondence between the game and ABM in GAM RDT 2 is not direct, as data observations from the game do not change the ABM. In this type, the ABM is developed to understand or analyse the decisions and interactions within the game, such as evaluating and comparing different theories on cooperation, group interactions, and collective decision-making.

Purpose: GAM RDT 2 is aimed at researching social interactions and the emergence of social patterns. GAM RDT 2 is particularly suitable for analysing data collected during gameplay and enables practitioners to explore game dynamics and gameplay through theory-driven explanations.

When to choose it: GAM RDT 2 is appropriate when researchers want to collect game data and analyse specific player decisions and interactions, such as studying the effects of changes in game settings. GAM RDT 2 can be selected for two main reasons: evaluating theories on cooperation, group interactions, and collective decision-making or supporting game development to enhance performance and calibration.

Strengths and *challenges*: One strength of GAM RDT 2 is the ability to execute the game and ABM research steps independently. The ABM and game are not directly connected, thus allowing flexibility in working with pre-existing or newly developed games and agent-based models. However, this flexibility can also be a weakness as the disconnection between the sequences may pose challenges in ensuring the validity of the collected game data and the effectiveness of the agent-based model when analysing the data.

Table 7 Examples of Publications that use GAM Research Design Type 2

Publication	Domain	Purpose
Tykhonov et al. (2008)	Supply chain model refinement through a cycle of validation, experimentation, and formulation of new hypotheses	Improving the understanding of human decision-making with respect to deceit, trust, and institutional arrangements for enforcing compliance
Dubois et al. (2013)	Natural resource management, attitude-behaviour relations, game setting effects	Stakeholder involvement, understanding the interactions between water-resource and water-use dynamics
Gomes et al. (2019)	Group management, serious games	Improving the collective ability of players to learn and train in multiplayer serious games

5.3.3. GAM Research Design Type 3: ABM → Game

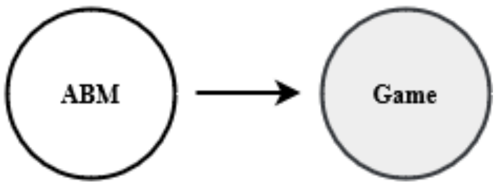


Figure 11 Prototypical Schemata of GAM Research Design Type 3

Sequence, target system, and correspondence: The sequence of GAM RDT 3 (ABM → Game) begins with an ABM phase and transitions to the game phase. First, an ABM of the investigated phenomenon is created (or a pre-existing one is selected). Subsequently, a game is created to mirror the model or highlight specific aspects of it. The game serves as a facilitation or data collection tool. It is primarily applied in co-design workshops for discussing system concepts in play-testing sessions or discussing elements of the model. The correspondence between the ABM and game is based on the fact that certain components of ABM are specified through gameplay. Researchers may use the ABM-to-game sequence repeatedly throughout the research process to gather additional information on model aspects.

Purpose: GAM RDT 3 is aimed at obtaining an understanding of particular phenomenon in a participatory process with stakeholders (in this regard, it is similar to GAM RDT 1). In GAM RDT 2, the focus is to improve an existing model of a target system.

When to choose it: GAM RDT 3 is appropriate when researchers want to access local or expert knowledge. The majority of research applications with this research design type are devoted to community-based approaches that engage stakeholders and improve communication between interest groups. It is also suited for improving existing agent-based models, as the knowledge gathered through the game can be used to verify (e.g., predictive ability), validate (e.g., ontology and dynamics), or calibrate the simulation outcomes.

Strength and challenges: *GAM* RDT3 is well suited to research that is aimed at improving a target system by engaging stakeholders in the research process. In terms of the use of RPGs, the strengths and challenges of *GAM* RDT3 are congruent with those of GAM RDT 1 (Section 5.3.1). An additional difficulty arises when transforming the agent-based model into a game. Agent-based models are often complex and can have several formal rules. Achieving the goal of creating a game that is both engaging and accessible to participants while accurately reflecting the underlying complex concepts requires the GAM practitioner to carefully create a balance.

Table 8 Examples of Publications that use GAM Research Design Type 3

Publication	Domain	Purpose
Lim et al. (2011)	Computer science, generative experimentation, social simulation	Stakeholder involvement, conceptual gaming framework for verification and validation of agent-based models
Joffre et al. (2015)	Natural resource management, shrimp aquaculture	Stakeholder involvement, improving communication and bridging gaps between farmers and policymakers
Le Pira et al. (2017)	City logistics, opinion dynamics	Stakeholder involvement, RPGs as a tool for validating agent-based models

5.3.4. GAM Research Design Type 4: ABM ↛ Game

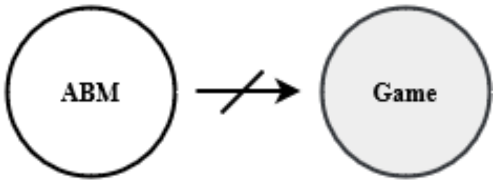


Figure 12 Prototypical Schemata of GAM Research Design Type 4

Sequence, target system, and correspondence: GAM RDT 4 (ABM ↛ Game) comprises a sequence wherein the ABM phase is initiated first, which is followed by the game phase. Both the ABM and game are separate applications, each serving specific research goals and designed with a particular target system in mind. The initial step involves creating an ABM or selecting a pre-existing one. Subsequently, a game is employed to gather additional data that can be fed back into the ABM. GAM RTD 4 often employs digital games wherein the player interacts directly with the computer. Digital RPGs (computer games) can be used as a data collection setup for testing different intervention scenarios with the players, and simple single-player or multiplayer games (e.g., anagram games) can be used in experiments to collect data for model evaluation and calibration of agent-based models or to extend the capacities of agents to make them more “human-like”.

Purpose: GAM RDT 4 is aimed at investigating human interactions, particularly in socio-technical systems. It allows practitioners to enhance or compare agent behaviours with human behaviours collected during gameplay.

When to choose it: GAM RDT 4 is well-suited for validating agent behaviour and introducing new dynamics into existing models. This is particularly valuable when researchers aim to enhance the accuracy of their models by incorporating agents that more realistically represent human behaviours. Furthermore, games can be used to explore questions that arise during the design or study of the simulation outputs. In this context, the link between simulation outputs and gameplay observations provides new perspectives on research problems (e.g., through triangulation).

Strengths and challenges: GAM RDT 4 employs stricter controlled setups during data collection than GAM RDT 1–3. Although this may limit players’ choices and actions, it enables researchers to replicate the game with different players and thus assess the consistency of findings across various data samples and enhance the result reliability. The controlled setting also reduces the likelihood of external game influences interfering with the study, which is particularly important in researching complex systems wherein isolating the direct effect of a specific variable on the observed behaviour can be challenging. However, the controlled setting may oversimplify and distort real-world complexities, thus restricting players to a limited and simplified range of possible actions. Another challenge of GAM RDT 4 is the increased demand for skills and preparation time required to create both an agent-based model and a digital game.

Table 9 Examples of Publications that use GAM Research Design Type 4

Publication	Domain	Purpose
Schill et al. (2016)	Collective action, sustainable resource management	Behavioural common-pool resource experiments for informing agent-based models
Bhattacharya et al. (2019)	Group formation in social and technological networks	Studying the dynamics of human-agent collectives in games
Cedeno-Mieles et al. (2020)	Collective identity, ABM	Online social experiments and online game platforms for evaluating network-based agent-based models

5.3.5. GAM Research Design Type 5: Game + ABM

Figure 13 Prototypical Schemata of GAM Research Design Type 5

Sequence, target system, and correspondence: GAM RDT 5 (Game + ABM) involves the simultaneous using of a game and an ABM. The game serves as an engaging workshop setting, while the essential game mechanics are incorporated via ABM. The ABM functions as a (sub-)component of the game, making it an integral part of both the game and its development. In GAM RDT 5, the game and ABM correspond directly. During gameplay, the agent-based model simulates complex mechanics, such as dynamic effects resulting from player interactions, to update game world parameters and present the updated values to the players. As a result, the target systems in GAM RDT 5 may be either equivalent or different, depending on the simulated effects required to support the gameplay.

Purpose: The purpose of GAM RDT 5 is to establish participatory research settings through the use of dynamic and responsive games. The game provides an engaging setting, while the fundamental game mechanics are integrated into the agent-based model. GAM RDT 5 enables the acquisition of stakeholder knowledge, fosters participant social learning, and facilitates the data collection of players' actions.

When to use it: *GAM* RDT 5 is typically used in workshops on community-based approaches and stakeholder approaches. It allows researchers to observe player behaviours and their reactions to parameter changes. In community-based approaches, GAM RDT 5 can allow for games that integrate complex mechanics while simultaneously enabling the players to concentrate on their tasks without being overwhelmed.

***Strength and challenges**:* GAM RDT 5 offers participants highly engaging settings by integrating gameplay and simulation elements, thus resulting in immersive GAM applications. It shares similar strengths with GAM RDT 1 and 3 but stands out by enabling the representation of complex and dynamic systems that are challenging to capture using games without ABM support. Working with GAM RDT 5 presents a distinctive challenge related to the significance of ABM-generated player feedback, as any errors or biases in the agent-based model can impact the players and significantly influence the outcome of the GAM research study.

Table 10 Examples of Publications that use GAM Research Design Type 5

Publication	**Domain**	**Purpose**
Adamatti et al. (2005)	Natural resource management, water management	Stakeholder involvement, facilitating the negotiation process between several stakeholders
Rouan et al. (2010)	Natural resource management, biodiversity	Stakeholder involvement, understanding vegetation dynamics in relation to social practices, development of management strategies, analysis at various temporal and spatial scales
Daré et al. (2018)	Natural resource management, water resources, governance, management	Stakeholder involvement, testing the willingness of different individuals and organisations to contribute to the activities of a multi-level bridging organisation

5.3.6. GAM Research Design Type 6: GAME = ABM

Figure 14 Prototypical Schemata of GAM Research Design Type 6

Sequence, target system, and correspondence: GAM RDT 6 follows a sequence wherein a new application is created from scratch, an existing ABM is transformed into a game, or a digital game is modified by integrating agent-based mechanics. In this design, the ABM and game are fully merged or integrated and comprise one single application. Their components are intertwined and encompass the application's mechanics, rules, and user interface(s).

Purpose: The aim of GAM RDT 6 is to provide an agent-based infrastructure for game interactions and play. It allows players to act within a simulation and interact directly with agents. It is suitable for allowing players to explore different development paths and counterfactuals of a target system,

When to use it: GAM RDT 6 is suitable for decision support tools in community-based approaches but also for researching human behaviour and socio-technological systems.

Strengths and challenges: The integrated approach of GAM RDT 6 addresses the challenge of efficiently transferring data between the game and ABM component of a GAM. By merging/integrating the game and ABM, GAM RDT 6 reduces the gap between the agent-based model and player behaviour. As all the interactions are computer-mediated, they can be recorded and processed, which benefits both participants and organisers. GAM RDT 6 designs also allow for computer-based enhancements, such as incorporating agents with AI-supported learning capabilities. However, the integrated design also limits the range of possible player actions. In contrast to RPGs, wherein players can be creative in their actions, all the actions in an agent-based game are required to be implemented in the software.

Table 11 Examples of Publications that use GAM Research Design Type 6

Publication	Domain	Purpose
Kleczkowski et al. (2015)	Public health, epidemics, virtual experiments	Studying human behaviour and investigating the relationship between self-protective behaviour during epidemics and cost
Guyot & Honiden (2006)	Natural resource and risks management, validation	Participatory experiments, studying negotiation in an abstract case of common resource pool management
Nguyen-Duc & Drogoul (2007)	Air-traffic management, user-centred design, participatory social simulation	Stakeholder involvement, dynamic RPG with software agents from ABM that interact directly with players

6. Example of GAM Research Design

This section presents an example of a GAM RDT 6 (ABM = GAME). The selected example is based on the study of Szczepanska et al. (2022b), which employed the co-self-study method to produce a description of the process of creating *Quantum Leaper* (*QL*), a 3D first-player computer game. This section provides insights for everyone interested in designing and conducting research using GAM RTD 6, particularly modellers and game designers. It provides background information on the GAM research components and their correspondence and discusses the development steps of *QL*. The GAM DS and GAM RF (Section 5.2) are applied in the example. The GAM DS provides detailed answers to methodological questions regarding the research design, and the GAM RF is used to unpack the interdisciplinarity process behind the study.

The *QL* is a proof-of-concept video game used to explore the potential of embedding an agent-based model into an immersive player experience for applications in archaeology. The *QL* was designed to test whether a game with ABM mechanics can contribute to understanding the factors behind the collapse of the Ancestral Puebloans via immersive exploration, discovery, and interaction with non-player characters (NPCs) and the 3D environment (Angourakis, 2021).

The game is based on the NetLogo implementation of the Artificial Anasazi (AA) model and is implemented with the Unity game engine. Basing the design on existing agent-based models reduces the time and effort required for designing, building, calibrating, and validating the model. It also has the benefit of relating the research design to existing bodies of knowledge, which helps to ensure the quality of the created application and allows the developer to test the new implementation against the existing model.

The *QL* was developed as a side project and remained a prototype owing to the missing resources required for implementing a polished application. Creating a 3D first-person GAM application that blends game and ABM elements requires a deep understanding of both domains and how they could work together to create a distinctive and immersive experience capable of representing and exploring intricate real-world phenomena. The implementation of such an application demanded a diverse set of skills, including programming, visualisation, and both qualitative and quantitative data analyses. Nonetheless, this application is a good exemplar for demonstrating GAM RDT 6.

GAM research components and their correspondence: AA is a simulation model that examines Arizona's Long House Valley population dynamics from 800 to 1350 AD. It explores the hypothesis that climate change caused the abandonment of the valley by linking a population of households with a simplified maize-based food economy that depends on soil types and humidity conditions. The model's simulations were evaluated by comparing them to the historical population size and distribution estimates per year. The original authors of the model concluded that climate change alone could not explain the valley's abandonment. The 3D computer game implementation adds game-design elements to the simulation model. It has a game interface that allows players to interact directly with agents and explore the environment of the simulation model from a first-person perspective. Furthermore, the game introduces dense visual and narrative storytelling that draws inspiration from the 90s television series "Quantum Leap".[6]

In *QL*, players find themselves as a time traveller in the consciousness of a historic person after a lab accident that has reshaped the course of history. The player can inhabit the consciousness of different historical individuals who lived in Arizona between 800 and 1350 AD. Their primary objective is to restore the disrupted timeline and reveal the secrets surrounding the lab accident. Through engaging interactive fiction and meaningful dialogues with NPCs, players wield power in shaping the storyline. The game offers an expansive open-world environment that encourages exploration, enabling players to interact with their surroundings and diverse generations of NPCs. By influencing the decisions and actions of the characters they inhabit, players have the ability to redirect the flow of history itself. Along their journey, players are accompanied by Gravy, an AI companion who provides guidance and reveals crucial information about the protagonist's future. Players must make strategic choices that have far-reaching consequences by carefully monitoring the outcomes through information provided by Gravy. By repeating jumps between Limbo (a meta space that allows the player to access the current state of the target system) and the past, the player can

[6] "Quantum Leap" is an American science fiction TV series that was broadcasted between 1989 and 1993. The story revolves around a physicist who travels through time by inhabiting other people's bodies to correct historical mistakes (Wikipedia contributors, 2023).

experiment with different strategies and points of intervention. Ultimately, success lies in their ability to recover the integrity of their original trajectory and restore the timeline to its rightful order.

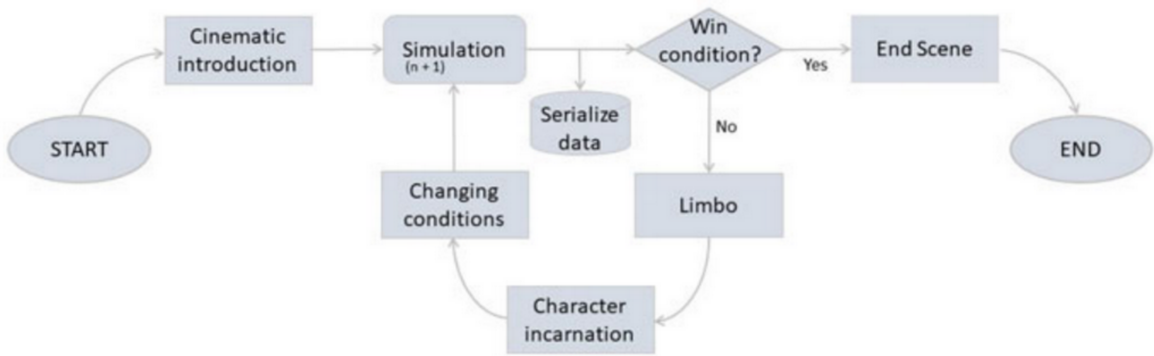


Figure 15 Quantum Leaper Game Flow

The goal of the ABM is to balance the game's mechanics with the historical context and extends over several centuries. It simulates player feedback and generates path-dependent trajectories for development scenarios depending on player actions. The ABM serialises and de-serialises simulation data into binary files, which are rewritten every time the simulation is run from an earlier year. This integration of the ABM and game builds the core for immersive player experiences that are not only entertaining but also educational. The ABM generates rich and meaningful game content, providing players a deeper understanding of the target system and its historical context. The interactive nature of the game, coupled with the computational power of the ABM, allows players to actively participate in simulations and observe the dynamic outcomes of their decisions. This hands-on engagement allows players to obtain a more profound understanding of the underlying processes, thus fostering a sense of agency and facilitating experiential learning. Players can explore and experiment with different scenarios through gameplay, uncovering new insights and gaining first hand-experiences with the intricacies of the complex phenomena they are interacting with. An overview of the interactions between the game and ABM is presented in Figure 15. The full description of *QL* is presented in Table 11. More information on the *QL* can be found in the studies of Angourakis (2020, 2021) and Szczepanska et al. (2022b).

Table 12 GAM Documentation Scheme of the Quantum Leaper Research Design Type 6. The table provides an overview of the research design of the QL agent-based game. The overview follows the GAM DS to provide detailed information on QL and its components. The document is divided into four sections. Each section provides answers to questions on a different level (the study, GAM, game, and ABM).

A) General aspects	1. Purpose of the study - Explore the potential for integrating ABMs and video games for immersive player experiences in the field of archaeology 2. Research questions of the study - Can ABM lead to new insights into the target system it presents? 3. Application field - Archaeology 4. GAM research design type - Type 6, Game = ABM 5. Additional comments - GAM RDT 6 offers a way to connect with a larger audience outside of academia. Its interactive and immersive quality appeals to a diverse range of players, including those who are not typically interested in scholarly research. This wider reach allows for the sharing of archaeological knowledge in a more accessible and engaging manner, thus making it available to a broader public.
B) GAM	1. Purpose of using the GAM methodology - A playable simulation for players to engage with a historical population of Ancestral Puebloans. Players learn about archaeological findings and may contribute to new knowledge. 2. What is the GAM research design? - The game and agent-based model are merged into one 3D computer game. *QL* used the existing AA ABM as a starting point. 3. How are the game and ABM linked? - The agent-based model and game are merged into one application. - At each turn (incarnation), the player influences model parameters; after the player completes a turn, the ABM simulates a new trajectory based on the player input. The player can then choose a starting point on the calculated trajectory for the next incarnation (Figure 15). - All components of the *QL* are programmed in Unity. 4. Limitations of the specific GAM research implementation. - *QL* allows players a limited set of actions through the use of the game interface. - The high development effort of the *QL* may outweigh the positive effect of using a GAM RDT 6 for research. 5. How did using GAM research contribute to answering the research questions of the study? - The project has demonstrated that it is possible to recreate the ABM in Unity. New computational methods have been created in Unity that recreate the scheduling processes common in ABM simulations. - Results according to the effectiveness of GAM RDT 6 for exploring the target system are limited because *QL* is still in its beta version. Experiments on the effectiveness of this specific GAM RDT implementation have not been conducted yet. 6. Advice for other researchers - The development of a first-person ABM-game requires a significant amount of time, especially as it cannot be implementation in a standard ABM platform such as NetLogo. Commercial games are usually developed with large teams that work on the project for several years. The lack of a large team for implementing such an application could be an obstacle for a scientific application.

7. Additional comments
   - *QL* is in a prototype state and has not yet been published as a game. It still requires improvements in the functional system and text base to handle dialogues.

C) Game

1. Target system
   - Arizona's Long House Valley population dynamics from 800 to 1350 AD
2. Kind of game
   - The game was built from scratch for the purpose of this study.
3. Game type
   - 3D computer game with a first-person perspective.
4. Game category
   - RPGs and simulations, adventure/sci-fi game
5. Who are the players (e.g., stakeholders, students, fellow researchers, general public)?
   - Thus far, *QL* has been played by researchers and archaeology students.
   - All players participated in the beta testing.
6. How were the players selected?
   - All the players participated voluntarily in the testing.
7. Game objective
   - To influence an agent population to recreate historic settlement patterns.
   - To explore path dependencies and the influence of individual actions on the states and dynamics presented by the target system.
8. What are the core game mechanics?
   - <u>Interaction:</u> The player interacts with the game world and non-player characters (agents) through dialogue and interaction.
   - <u>Game objective:</u> The player must find a solution to approximate the current population trajectory to the historical trajectory provided by archaeological data. Players can revisit selected points in a timeline to engage with the current generation of the agent population. When the player succeeds in creating the historical timeline, the winning condition is met.
   - <u>Contest:</u> (1) Players can compare their performance (with themselves, computer opponents, or other players). (2) Various difficulty levels can be set by changing the start condition and win/lose conditions as differences between current and historical trajectories.
   - <u>Decisions:</u> (I) The players decide which time steps in the simulation they want to revisit. (2) Players are required to set a general objective according to which they want to influence the system dynamically. (3) Players are required to find a dialogue strategy to effectively influence the agents.
9. What data are collected from the gameplay?
   - The game collects player interactions with agents and data such as agent and environment parameters every time the player enters Limbo.
   - During Limbo, the ABM calculates path-dependent trajectories for the development scenarios. During the simulation, all the system states are collected for each time step. This allows players to revisit different time steps of the simulation.
10. How are the data collected from gameplay (e.g., observation, tracking, etc.)?
    - The data are recorded by the Unity implementation during the gameplay.
11. If debriefing was performed, how was this done? (If debriefing was not performed, provide a reason for that decision.)
    - Debriefing was used by the original developers to reflect on the different development steps; furthermore, a co-self-study was performed (Szczepanska et al., 2022b).
12. What data are collected after the gameplay?
    - Thus far, no experiments have been conducted with players.
    - Collection of data regarding experiences gained with the target system is planned.
13. How are the data collected after the gameplay (e.g., questionnaire, interview, and focus group)?

- Questioners and interviews are feasible methods, but suitable collection methods have not yet been developed.
- Debriefing is intended to improve the effectiveness of learning.

14. What does the game add that would not be known otherwise?
    - The game adds a narrative, dialogue system, 3D visualisations, audio and sound design, game world design, controls, and a reward system to the simulation. The combination of narratives with simulation and prediction improves decision-making and strategy development in wicked systems.
15. Additional comments
    - In the original AA model, the population is represented as households, while in *QL,* the player interacts with individual agents. This challenge was met by assigning groups agents as belonging to a household.

D) ABM

1. Target system
    - The ABM is an integral part of the game. It is based on the AA ABM, which represents the population dynamics of the Long House Valley between 800 and 1350 AD.
2. Link to fill in documentation/reporting protocol/scheme
    - https://jasss.soc.surrey.ac.uk/12/4/13.html
3. What does the ABM add that would not be known otherwise?
    - The ABM mechanics are used in the *QL* GAM research implementation to calculate direct player feedback; it is used to time travel by simulating the effect of player interactions with other agents on population dynamics.
4. Additional comments
    - AA was selected as the model because it is well-documented and has a topic related to archaeology.
    - During the development of the Unity implementation of AA, multiple problems with the NetLogo implementation of the AA mode had to be addressed: (I) The input data used for the AA included misplaced water points and historical settlements. (2) The maise stock inheritance between agent generations was flawed. A model parameter sets how much maise the parent household transfers to its child household. However, the child household received a maise amount unrelated to this parameter.

GAM development: To create the *QL* as a GAM RDT 6, the development comprised three steps: (1) the ABM replication, adaptation, and extension, (2) the GAM conceptual design, and (3) the implementation of the GAM application.

(1) The ABM replication and extension: To create a GAM RDT 6, it is necessary to use a universal programming language to program an application that contains both ABM and game components. The first step of creating *QL* was translating the original NetLogo model of the AA into Unity using the C# programming language. In contrast to NetLogo, Unity is not specially built as a *multi-agent programmable modelling environment*. Therefore, it was necessary to create C# libraries that control ABM-related agent scheduling and data processing. Code reviewing is a crucial aspect of the translation process, and it helps to optimise the new implementation and identify any bugs in the original code.

(2) GAM conceptual design: On referring to the definition of GAM research (Section 3.1.3), a computer game can be considered as an agent-based model with better graphics and less social theory, while an agent-based model can be considered as a computer game with theory-driven dynamics but without elaborate game-design elements. The *GAM RDT 6 is a game with social-theory-driven dynamics and elaborated game-design elements*. Hence, in this step, the Unity ABM is extended with the four-game design elements (Schell, 2019). The underlying technology and aesthetics of the game are considered (Figure 3). *QL* is a first-person game programmed in Unity. The visual aspects of the game include 3D visualisations of characters (players and NPCs), households, the environment, and user-interaction elements such as dialogue boxes and statistical information on the state and trajectories of the simulated system. Moreover, the game mechanics related to the rules and interactions that govern gameplay are addressed. This involves designing the core mechanics (Table 12), gameplay loops (Figure 15), player controls, and a dialogue system. Mechanics are also responsible for defining how players can interact with the game world and how the game responds to their actions. Furthermore, the story of the game is being taken into account. Creating a narrative for the game includes developing characters (players and NPCs/agents), a plotline, setting, and any other storytelling components. The story can be conveyed through cutscenes and dialogues. This adds depth to the emotional engagement of the player.

(3) GAM development and model extension: The GAM development process included various tasks such as managing simulation data, designing the 3D landscape, creating a dialogue system, and producing artistic assets. The development team faced challenges in configuring the 3D space with spatial data and developing a dialogue system using Twine-Tracery (*Twine* is an open-source application for interactive, nonlinear story-telling). They also used Unity's "Asset Store" for audio-visual elements and designed a minimal user interface and game system. Finally, the original agent-based model was modified to better fit the overall game design, including improvements in the model trajectories and changes in agent representations.

Combining ABMs and games in a GAM RDT 6 requires skills from different disciplines. The example promotes cooperation between archaeologists, historians, social scientists, and game developers to create accurate and authentic virtual environments that reflect historical contexts. The expertise of scientists of different domains in constructing ABMs can improve the accuracy and reliability of the simulations. At the same time, game developers can contribute to crafting narratives and captivating gameplay mechanics. Nevertheless, GAM RDT 6 also demands improvisation from the researchers involved. In interdisciplinary teams, researchers should expect to encounter unexpected challenges. Contrasting scientific paradigms could force researchers to cross subject boundaries to create new knowledge, theory, and methods and solve a common research goal. Venturing in such uncharted terrain has its risks. The resulting applications may exhibit unintended dynamics, or the research designs may not yield the expected results. The GAM RF provides a tool to help unpack these issues (Table 13).

Table 13 GAM Reflection Framework for GAM Research Design Type 6 on the Example of Quantum Leaper (Szczepanska et al., 2022b)

Part 1: Formal reflections

WHAT contributes to GAM	
What disciplines and knowledge bodies were involved and integrated?	
In the ABM	Archaeology, expertise of ABM modellers
In the Game	Archaeology, game design, expertise of native communities (at a future point) and expertise in the various implementation tools (e.g., Unity)
HOW GAM is performed	
Which resources were used? Explain why these were used.	
Empirical (datasets and sources)	Spatial data files given with the NetLogo implementations of the model; height map (or digital elevation model) of the location (Longhouse Valley, Arizona, USA). Source: USGS, through terrain, party.
Methodological (methods)	ABM; game design for creating. open-world 3D first-person games, general storytelling techniques (e.g., rhythm and plot devices), and visual storytelling.
Theoretical (theories)	Knowledge used for reviewing and extending the AA model: complex adaptative systems; human ecology and demography.
Technical (tools)	NetLogo (ABM preparation); Unity and C# (game development); Twine-Tracery (interactive text system); Terrain.party (obtaining terrain heightmap); GIMP (image editing); Audacity (audio editing); Free Music Archive, SoundCloud, Freesound (obtaining sound effects and music).

WHY GAM is used

What new knowledge is produced by the GAM design? What problem is it aimed at solving?	
Epistemological (to produce new understanding and knowledge)	Experience a multiagent system from a first-person perspective; to obtain new insights about the model and the dynamics of the systems it aims to represent.
Instrumental (to solve a problem or a societal challenge)	Bridge the gap between the formal, unintuitive definition of complex socio-ecological phenomena found in ABMs and the more general understanding of how society relates to environment, particularly, but not only, by non-modellers.

Part 2 General reflections

Team (organisation, communication, etc.)	*QL* was developed by a two-person team working mostly side-by-side on different tasks. It was apparent that the team lacked some key skills, particularly those of a trained artist and writer. The majority of the work was carried out in Unity, and, at that time (2017), sharing Unity projects in an orderly manner was more challenging than today. Unity now offers a built-in cloud service with version control, using which collaborators can work on the same project.
Game engines or platforms (pros and cons, challenges, etc.)	Unity is one of the most comprehensive and accessible game engines available at present. The *QL* prototype was developed relatively quickly owing to this and given the vast online community of users sharing Unity assets, including C# code snippets. However, it is a tool that undergoes constant change and improvement, thus making learning new features a never-ending necessity. Undertaking some type of formal learning (e.g., massive open online courses) is recommended to use this tool at its full potential.
Transparency and rigour (measures taken etc.)	The development team maintained an ongoing design document wherein notes about advancements and new ideas were stored and shared. The code base of the ABM and game system has been constantly tested, refactored, and annotated, with the aiming of making it reproducible and readable for the wider public. Screen video recordings were created after different milestones in development and shared on YouTube.
Stakeholders (interaction, etc.)	(Pending until after the game is published.)
Outputs/outcomes (what was produced, how it was received, etc.)	(Pending until after the game is published.)

7. Discussion, Conclusion, and Future Work

The versatility, scalability, and capacity of GAM research make it an exciting and promising research field. GAM research contributes to the development of a robust evidence base for informed policy decisions and advances our comprehension of complex systems. The combination of games and ABMs in GAM research provides a powerful platform that blends entertainment, education, and research. Practitioners of GAM research can create immersive experiences for players while enhancing their understanding of intricate systems. Nevertheless, the implementation of GAM research involves significant challenges. This thesis presents methodological guidelines for designing and conducting research using combinations of games and agent-based models, i.e., the GAM methodology. The thesis serves as a handbook and provides inspiration and references for researchers. It sets the theoretical background of GAM research, explores various research designs, and offers practical advice. In this thesis, I followed examples of other disciplines wherein methodological works shaped and refined an existing approach and helped researchers to find common practices.

The thesis begins with an analysis of the state of GAM research and the tracing of its origins and advancements over the past 23 years. Examples of studies analysed in this thesis have been employed in many application domains for diverse reasons; among other things, studies were focused on investigating mental models, predicting future system states, creating development scenarios, and providing policy advice. I observed that many current publications ignore the broader field of GAM research beyond their scientific niche, and they thus lack interdisciplinary awareness, which limits their research's full potential. By acknowledging the wide range of GAM research in various disciplines, researchers could benefit from cross-domain insights, collaboration, and knowledge sharing. The current lack of a standardised methodology for GAM research often results in publications with inadequate descriptions of crucial study elements, such as game or ABM designs. This thesis is aimed at bridging this gap by providing researchers with a theoretical and practical background for enhancing their understanding of GAM research by providing a knowledge corpus to root future research in. This GAM methodology also introduces measures for enhancing rigour, transparency, and replicability, thus promoting wider adoption and engagement beyond the academic community. The interactive and compelling nature of games attracts diverse players, including those who may not typically be interested in scholarly research.

The latter half of this thesis offers practical advice for practitioners and outlines the different steps involved in the design process. It emphasises the fundamental concepts to be considered when combining games with ABM. It provides guidelines that help researchers think about GAM and its ABM and game components, in addition to their sequences and correspondence. This thesis also makes an effort to improve research transparency and reproducibility by providing frameworks for documenting and reflecting on the research process. It should be noted that it introduces six research design types that researchers can use as blueprints for their studies, thus serving as a practical resource for guiding their research endeavours.

I envision this thesis as a starting point for refining a general *methodology for designing and conducting research that combines games and agent-based models*. This foundational work is a step forward in establishing a general methodology that transcends disciplinary boundaries. This thesis was inspired by the work of Cresswell & Clark (2017), "Designing and Conducting Mixed method research". Their book is an ongoing effort to structure and re-structure the knowledge on mixed-method research. Similarly, I hope the GAM methodology will evolve through collaborative efforts and be adopted, extended, and refined over the coming years. The thesis may also be interesting to the broader ABM community. At its core, GAM is a mixed-method approach. Concepts from this thesis can be repurposed to describe any method combination that contains at least one ABM component, e.g., the categorisation of GAM RDT can also be applied to describe research designs that combine ABM and real-time surveys.

One conclusion drawn from laying the foundations of GAM research is that developing the GAM methodology, researching its potential with case studies, and evaluating its effectiveness goes well beyond the scope of a PhD project. The potential of GAM for researching not only SECAS but any social complex systems shows that significant investments in effort and funds would be well spent on promoting GAM in large-scale interdisciplinary research projects.

Given the present global situation, I find it perplexing that investments in science are shrinking, especially with regard to supporting and embracing new, innovative methods to research the complex workings of social systems and their interconnectedness with the existing world. Modern societies confront many complex challenges that appear to have no easy solutions. Social crises, climate change, loss of biodiversity, and deterioration of marine ecosystems are just a few of the issues that must be addressed (Quinlan, 2020). The Sustainable Development Goals tracker (SDG-Tracker) from the Our World in Data database suggests that humanity is struggling to address global challenges successfully. GAM research is an instrument that has the potential to contribute to addressing these problems using complexity sciences, participation, and a new unique method of experimentation.

Elaborate GAM research designs allow participants to react to "realistic or accurate" situations with justifiable actions based on prior experiences; but GAM research goes beyond this. For example, a GAM RDT type 6 allows participating players to behave in realistic ways (in comparison to other methods such as lab experiments, surveys, or interviews). It allows them to test new behavioural strategies in the game world without impacting the real world. This can allow researchers to collect a richer set of behaviours from observation and compute, identify, and compare possible, probable, preferable, and disruptive future scenarios, ultimately providing sounder predictions on the impact of human interference with the world and possible pathways for a more sustainable future for humanity. This potential makes GAM an extraordinary method that could revolutionise how we conduct social science and provide us with a method of researching social phenomena beyond the capabilities of games, ABM, or experimentation alone. Investing in GAM research would greatly benefit science, citizens, and society. However, to enable such a vision for GAM research, we need resources beyond those of small-scale projects, single efforts, and side projects. We need investments that allow for multi-year studies with interdisciplinary teams of researchers and societal participation. As the call for investments on a large scale is far-fetched and requires an immense impulse from the institutional side, I suggest four interim research efforts that can improve the GAM methodology and advance the research beyond its current scope:

(1) The provision of an in-depth analysis and description of all six GAM research design types, including implementation examples with case studies.

(2) The development of standards for the different research steps of GAM research, including instructions on collecting data, analysing and interpreting results, and evaluating the impact of GAM studies.
(3) Improvement in the cooperation between practitioners from the ABM and games communities to create efficient and effective GAM research applications. This process can be facilitated by providing infrastructure for facilitating discussions, such as repositories of best practice examples and templates for increasing transparency in the field and the reproducibility of GAM research. In this thesis, the introduction of the GAM DS and GAM Reflection Framework provided a first step in this direction.
(4) It would also be interesting to investigate how machine learning can improve GAM research, especially in overcoming time constraints. Chat-GPT or other text-to-speech programs can provide creative ways to create intuitive human-computer interfaces or automate programming and game-design processes.

8. References

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Paper 1

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Sensemaking of causality in agent-based models

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ABSTRACT

Even though agent-based modelling is seen as committing to a mechanistic, generative type of causation, the methodology allows for representing many other types of causal explanations. Agent-based models are capable of *integrating* diverse causal relationships into coherent causal mechanisms. They mirror the crucial, multi-level component of emergent phenomena and recognize the important role of single-level causes without limiting the scope of the offered explana- tion. Implementing various types of causal relationships to complement the generative causation offers insight into *how* a multi-level phenomenon happens and allows for building more complete causal explanations. The capacity to work with multiple approaches to causality is crucial when tackling the complex problems of the modern world.

KEYWORDS
Causality; agent-based modelling; complexity

Introduction

The majority of present-day societal challenges (e.g. adapting to climate change, protecting biodiversity, living in greener cities, managing a pandemic and ensuring soil health and food security) require not only novel technological breakthroughs, but also a deeper understanding of multilevel social phenomena. Agent-based modelling (ABM) is widely seen as an inter- and/or transdisciplinary methodology that is able to provide insight into such phenomena through representing the way multilevel, complex systems operate. In this article we argue that, even though ABMs are primarily perceived as committing to a mechanistic, generative type of causation, the methodology allows for the integration of other types of causation in a single research endeavour.

The next section briefly describes the sociological approaches to investigating multilevel phenomena, and concludes by highlighting the importance of mechanism-based explanations. Section 2 summarizes the stance that ABMs provide mechanistic, generative explanations of multilevel social phenomena. In section 3, we substantiate and augment that claim by showing how ABMs have successfully represented various types of causal mechanisms in the past. We conclude by making a normative claim: that ABM not only can, but should, use all available information about causal mechanisms in its attempt to build better models of multilevel social phenomena.

1. Sociological approaches to studying multilevel social phenomena

Investigating multilevel social phenomena has historically been the domain of sociology. The linkages between micro- and macro-levels have fascinated sociologists for decades and are still hotly debated in sociological theory. Even though *sociological theory has not resolved its micro-*

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macro divide any more than other sciences (. . .) sociological theorists seem rather more obsessed with the problem (Turner, 2001, p. 6). Multiple theoretical camps in western sociology re-formulated the micro-macro distinction into the division between agency and structure, and began arguing which is more important. *Micro-chauvinists* argue for the primacy of agency – it is action that gives rise to macro-level forces. *Macro-chauvinists* emphasize the constraining force of structure and culture that make individual actions predictable. Unsurprisingly, while there were polarizing views on which preceded the other, there was also an attempt to establish a middle ground (e.g. Archer, 1982; Barnes, 2001; Giddens, 1984). In the 1980s, the agency-structure primacy discussion settled with a compromise, at least for a brief period.

Over last two decades, a new and promising direction for investigating multilevel phenomena materialized. Mechanism-based explanations seized the social scientific spotlight (Hedström, 2005; Hedström & Ylikoski, 2010; Pozzoni & Kaidesoja, 2021). They did not explicitly commit to a micro-chauvinistic stance as their advocates do not use terms such as agency or structure. Nonetheless, it is hard to overlook the bottom-up emphasis of the approach, according to which a sufficient explanation has to uncover a mechanism, the *cogs and wheels* underlying the investigated phenomenon (Hedström & Ylikoski, 2010, p. 50).[1] In a functionalist interpretation, a mechanism is a *structure that performs a function as a consequence of its component parts, component operations, and organization* (Bechtel & Abrahamsen, 2005, p. 423). The focus on mechanism-based explanations in social sciences follows the rise of analytical sociology, a school of thought advocating the rejection of black-box explanations such as congruence-law or statistical explanations. According to analytical sociology, a sufficient explanation should pay attention to the process details of a social phenomenon to underpin how explanans and explanandum are linked together (Hedström, 2005). This line of thinking is rooted in structural individualism according to which a*ll social facts, their structure and change, are in principle explicable in terms of individuals, their properties, actions, and relations to one another* (Hedström & Ylikoski, 2010, p. 60). Thus, a mechanistic explanation requires the commitment to structural individualism – the mechanism must be composed of individuals, their properties, actions, and relations to one another (Pérez-González, 2020). Thereby, the mechanism-based approach describes a dynamic causal process that generates the effect of interest (Hedström & Manzo, 2015), instead of providing an exhaustive account of all details of the full causal story (Elsenbroich, 2012). Agent-based modelling, a methodology aligned with the principles of structural individualism, was an important contributor to the rise of analytical sociology, as it offers mechanistic explanations of multilevel social phenomena.

2. ABMs as generative explanatory models of multilevel social phenomena[2]

Scientific explanations are answers to certain kinds of 'why' questions (Salmon & Salmon, 1979, p. 62). It is widely accepted that explaining a phenomenon means providing a causal account for it.[3] Before we outline how agent-based models represent a specific, well-defined approach to causality, a short and more general note displaying the plurality of existing approaches is given. Among others, theories and/or models of causal inference and explanation include regularity theories (Hume, 1739 [1978]), the deductive-nomological model (Hempel & Oppenheim, 1948), the inductive-statistical model (Hempel, 1965), the statistical relevance model (Salmon, 1971), counterfactual theories (Lewis, 1973), the INUS model (Mackie, 1974) and mechanistic theories (elaborated on below). These competing approaches propose different ideas about what can be defined as a single and/or joint cause of a phenomenon and provide diverse structures for how explanation in science should be applied.

The ABM approach to explanation largely aligns with mechanistic complex systems theory.[4] In the version of the latter outlined by Machamer et al.'s (2000),[5] dualist mechanisms are composed of entities and activities (i.e. the dualism of entities and activities). While entities engage in change, it is the activities that are the producers of change. Therefore, a mechanism is not seen merely as a mechanical (push-pull) system, but rather as *entities and activities organized such that they are* *productive of regular changes from start or set-up to finish or termination conditions* (Machamer et al., 2000, p. 3). The organization of entities and activities matters in the way they produce the phenomenon of interest: entities must have specific properties and/or be appropriately located, and the activities must have a temporal order, rate, and/or duration. One of the central features of agent-based modelling is that the code is explicit about scheduling of the processes and the roles of various types of agents: at any given moment it is traceable which entity is undertaking what activity. Moreover, the ABM community strongly supports clarity in reporting a model's scheduling (e.g. by using flowcharts (Grimm et al., 2006) or pseudo-code (Grimm et al., 2010)).

In a mechanistic manner, ABMs explain macro-level phenomena by explicitly showing how they were generated through micro-level interactions: *The fundamental social structures and group behaviours emerge from the interaction of individual agents operating on artificial environments under rules that place only limited bounds on each agent's information and computational capacity* (Epstein & Axtell, 1996, p. 6). Early models supported the idea that no central control was needed to achieve a macro-level outcome, and simulating processes of emergence became a key characteristic of the agent-based modelling methodology. A widely cited example is the segregation model of Schelling (1971) and Sakoda (1971), which demonstrated how a fully segregated society could emerge despite only a slight preference of individuals to avoid becoming a minority in a neighbourhood. Another popular example is the flocking of birds, which mesmerised many people and provoked them to speculate about a *group intellect*. As it turns out, complex macro-level patterns could be easily grown from a few simple rules guiding individual bird behaviour (Reynolds, 1987).

There is a general consensus that emergence is by definition a feature of any ABM.[6] It is how we teach agent-based modelling and how we usually build models (e.g. Macal & North, 2010). Epstein (2006) coined the term *generative social science* to address the capability of ABMs to understand complex social phenomena by *growing* them in computer simulations. The idea, originating in the Santa Fe Institute, has dominated thinking about micro-macro linkages among agent-based modellers, and the perception of agent-based modelling among other scholars. The methodology is widely thought of as *a computational implementation of 'methodological individualism,' the search for the microfoundations of social life in the actions of intentional agents* (Macy & Flache, 2009, p. 245; but also e.g. O'Sullivan & Haklay, 2000). As a result, historically, agent-based modelling unjustly acquired a reputation of being a micro-chauvinistic approach, which is a rare achievement for a methodology that was not founded on any particular such theory. To this day, the field is dominated by models that strictly follow methodological individualism and give primacy to human agency. However, the mechanistic generative causation leading to emergence is not the *only* type of causal mechanism that agent-based modelling is capable of representing. Due to its multilevel nature, the methodology can also investigate how the macro-level phenomena impact the behaviour of individuals (often referred to as 'downward causation'). The beginning of the 21st century marked the start of a meaningful and noteworthy debate that recognizes the potential of ABMs to include downward causation and represent bi-directional causality (Conte & Castelfranchi, 1995; Conte et al., 2001; Sawyer, 2000). As a result of the debate, representing bi-directional causality was recommended as a standard guiding future work. For example, Conte and Paolucci (2014) argue for including bi-directional causality when representing social phenomena, and Filatova et al. (2013) when representing socio-ecological systems. Subsequently, examples of ABMs that explicitly implemented multi-level bi-directional causality materialized. Gilbert (2002) modified the Schelling/Sakoda model by adding a neighbourhood-level crime rate, that partially determined the price of housing in the neighbourhood, and restricted the new location moved to by the ratio of old to new property value. Implementing the emergent macro-level structural restriction of individual actions replicated the clustering pattern found in the original study. Conte et al. (2013) provided further examples of both simple and complex (i.e. second-order emergence and immergence) causal loops.

Similar feedback mechanisms and dynamic causal loops are distinctive features of complex social systems mimicked in ABMs (Conte & Paolucci, 2014), and have been previously recognized in sociological theory (e.g. Archer, 1982; Barnes, 2001; Giddens, 1984).

Examples in the last paragraph clearly indicate that the emergence-exclusivity of ABMs has already been contested. Scholars in the past focused mainly on the causal links between the levels, particularly acknowledging macro-micro, and bi-directional causal influences. The next section will further challenge the view that agent-based modelling is exclusively committed to a single account of causality i.e. to building mechanistic, generative explanations of emergent phenomena. We highlight the various within-level causal relationships that can be integrated in a complex mechanism represented by an ABM.

3. ABM as an integrative platform for causal relationships

> Every nut, bolt and washer in a laboratory instrument is the carrier of epistemological assumptions. Every aspect of design, data collection and analysis in social research bears a commitment to a particular model of social explanation.
>
> (Pawson & Tilley, 1996), p. 574

ABMs are capable of representing coherent and relatively complex causal mechanisms by serving as integrative platforms for causal assumptions adhering to various theories of causal explanation, not only to the mechanistic generative emergence. We begin this section by enumerating diverse interpretations of causal relationships that, alongside generative emergence, are popular in social sciences. We present examples of how causal relationships are expressed and point to some of the epistemological assumptions that may be underlying these expressions. Subsequently, to substantiate the claim that ABMs can serve as integrative platforms for diverse causal assumptions, we provide three examples of ABMs that successfully combined various modes of causation into coherent mechanisms without sacrificing the generative identity of the methodology.

The approach to causal inference taken by a given researcher is reflected in their research questions, and the subsequent choice of research design[7] (incl. the implemented research and data collection methods, and techniques to analyse data). The way we ask questions about reality determines the way we answer. The explanations scientists give are indicative of what they perceive as causes and effects, and as the appropriate manner to investigate causal relationships. However, the way that the explanation is formulated is determined *not only* by the research question (and the broadly-defined research design that followed), but also by the scientific background of the scholar, and the dominant idiosyncrasies of their disciplines, especially with respect to the preferred (formal) language to express casual relationships. For example,[8] physical sciences often describe causal relationships in the inorganic world by outlining deterministic formulas. The formulas often follow a deductive-nomological model of explanation (Hempel & Oppenheim, 1948), where the explanandum follows logically from the premises in the explanans (i.e. deductive) and one of the premises of the explanans is a law of nature (i.e. nomological). On the other hand, quantitative approaches in social sciences (e.g. methods and techniques such as experiments and survey questionnaires) usually analytically express social phenomena in a probabilistic manner (e.g. with the use of analytical techniques based on regression; Russo, 2009). There is a number of theoretical approaches to causality that a regression equation can follow. From Hempel's (1965) inductive-statistical explanations where the effect follows a cause(s), given a statistical law (i.e. with high probability, rather than universally), through Salmon's (1971) statistical relevance model where causes should *make a difference* to the occurrence or non-occurrence of the explained effect, rather than determine it with high probability, to Mackie's (1974) INUS model where a cause is an Insufficient but Nonredundant (necessary) part of a condition that is Unnecessary but Sufficient (e.g. a more complex, multivariate regression model with an interaction).[9] Experimental and quasi-experimental research designs can easily use causal effect or the counterfactual models of causal inference. In a nutshell, in counterfactual approaches the cause is *something that makes a difference, and the difference it makes must be a difference from what would have happened without it* (Lewis, 1986, pp. 160–161). The Neuman-Rubin causal model (Rubin, 1974) defines the causal effect as the difference in the effect when a cause is present, compared to a situation when the cause is absent, and in its extension by Holland (1986, also called the Neuman-Rubin-Holland model), elaborately deals with the fundamental problem of causal inference, namely the issue that direct observation of the causal effect is impossible (at the same point in time the actual state and the counterfactual state cannot not exist together e.g. John either took the medicine or did not take it). Mohr (1982) contrasts such *variance-theory models of explanation* present in quantitative social sciences with *causal processes* (Salmon, 1984) by which some events influence other events. The latter approach has been implemented in qualitative methods (e.g. case studies, in-depth interviews or focus group interviews),[10] although it is disputable if its author would agree with such implementations (Salmon, 1997). Furthermore, comparative studies make use of multiple conjunctural causality (Ragin, 1987). Similar to the INUS model, conjunctural approaches investigate combinations of causes rather than single causal influences, and employ Mill's (1843 [1967]) method of agreement and indirect method of differences to identify conjunctions of cases jointly sufficient for producing a given outcome.

ABMs explicitly define a *causal mechanism* responsible for eliciting the phenomenon under investigation. Micro-level interactions between agents responsible for eliciting the emergent macro-level phenomenon are the core part of that causal mechanism. This way, ABMs adhere to the principles of generative causation. However, ABMs can, and often do, incorporate other types of causation. This happens because elements of the mechanism (Bechtel & Abrahamsen, 2005), such as component parts (e.g. heterogenous agents of different types/breeds), component operations (e.g. actions of agents), and their organization (e.g. causal relationships between components) can be constructed with the use of information from other methods and techniques, even if those approach causality in different ways. We believe that the way causal relationships are expressed by non-modellers is crucial for this discussion, as it constitutes the foundation for the ABM inputs. Modellers most often do not have the opportunity to acquire a first-hand in-depth understanding of the causal relationships of a target system they want to include in the ABM. Consequently, in the quest to make sense of the represented reality and ascribe meaning to the models, they rely on what they manage to find in existing written accounts (empirical or theoretical). As the target system mimicked in the ABM is usually complex, to assure a sufficient level of resemblance modellers utilize all the causal assumptions they can get their hands on.[11] This process forces them to interpret the various languages causal relationship were formulated in. To back our claim with evidence, we present three examples of non-generative causal assumptions implemented in agent-based models: deterministic equations, probabilistic relationships and causal processes.

Example 1: deterministic equations in agent-based models

Classical physics aspires to provide us mortals with the Laws of Nature (well-established, empirically verified principles expressed in a form of equations e.g. Newton's law of gravitation, or his three laws of motion), which can be used to explain a wide range of phenomena. The existence of deterministic, universal laws feels warm and cosy, as it decreases uncertainties and offers psychological comfort. The determinism in classical physics is based on finding an existing, unique solution in the theory of ordinary differential equations (Clark, 1990). Using the Laws of Nature allows for building the covering-law models (Hempel & Oppenheim, 1948), where explanation of a phenomenon is given by a logical conclusion of a deductive argument with law statements and descriptions of initial conditions as premises. Recently, Polhill et al. (2021) show that there might be potential for building law-like principles also in the social world. Assuming explanation-prediction symmetry, the authors successfully demonstrate that neither complexity nor wickedness make finding a solution in a deterministic *isolated* complex system intractable, however endogenous ontological novelty in wicked systems renders prediction futile beyond the immediately short term. With less optimism, Elsenbroich (2012) argues that covering-law explanations (or, to be precise, *statistical explanations based on the covering law approach*) have limited usability in agent-based models that investigate underlying mechanisms and provide explanations of social phenomena, although they *can be used as evidence for causal associations* (ibid.). They can, and they indeed were. The examples in the ABM literature are plentiful. Here, we point to Marilleau et al. (2018), who simulated the spreading of a montane water vole (*Arvicola scherman*) population in the Haute-Romanche valley (France) by coupling ABM and EBM in a single multiscale model. Agent-based modelling was chosen due to its capacity to represent spatial heterogeneity (i.e. variation in topographic slope that restricts vole movements) and individual micro-scale behaviours (i.e. vole movements determining which agents can interact together and produce offspring). Equation-based modelling offered the analytical solution in the form of a logistic, age-structured population growth model. The submodel expressed how the change (growth) of the young vole population in each cell was determined by the number of voles inside the cell and the carrying capacity of that cell. Reflecting on future work, authors emphasized that other equations (e.g. representing a weather component or a more accurate predation model) can be added to the current model, although a significant challenge of maintaining coherence while increasing complexity would occur: *In this case, the model would include even more scales and would call for a specific organization of calculations and links between different scales* (ibid., p. 40).

Example 2: probabilistic relationships in agent-based models

Combining games with ABMs is still a relatively rare practice (for a review, see Szczepanska et al., in press in this special section of IJSRM). While games were initially applied in participatory modelling as a component of the model design phase, they can also be found as an integral part of an experimental setting. Researchers use experiments to study causal relationships by (1) manipulating the cause and observing the effects afterwards, (2) examining if variation in the cause is linked to variation in effects, and (3) reducing the plausibility of other explanations for the effects (Shadish et al., 2002). The examples of implementing probabilistic relationships in ABMs we give you here come from two studies that combined all three: games, experiments and agent-based modelling. Structural similarities between games and agent-based models allow researchers to operate in two counterpart realities: the game interface of the experiment and the agent-based computer meta-model. Observations from the gameplay are used twofold: (1) to determine probabilities of certain actions that are subsequently used in ABM calibration, and (2) to provide data for ABM validation that is achieved by comparing the simulations with experimental results. The ABM simulations are subsequently used to scale up the game/experimental results by expanding the parameter space. Bhattacharya et al. (2019) investigate the rationality of the decision-making processes of individuals located in social networks. In an online game, players of different colours communicate over their network links and exchange their locations (node positions). The goal is to switch network locations with other players to achieve global colour-clustering. Analysing experimental data with a logistic regression, researchers examine to what extent a player's ratio of sent requests to no request depends on factors like cluster size of the requesting player, cluster size of the requested neighbour, etc. (for a more comprehensive description, see the original paper). In what is labelled as a practice of *probability matching*, authors later use the probabilities of sending a request in various contexts (as defined by the independent variables of the logistic regression) to calibrate the decision-making of the agents. Once evaluated by fitting to the experimental data, the parameters in the ABM are used in numerical simulations as the agent behaviour baseline. Authors then scan the parameter space (by varying agent strategies) and compare the effectiveness of other possible strategies with the strategy employed by humans. Cedeno-Mieles et al. (2020) applied a very similar method combination to investigate how collective identity develops in groups. They also used a (multilevel) logistic regression to determine probabilities of possible actions taken by the players. However, by implementing a set of independent variables as a vector, the authors used a combination of probabilistic and configurational causality – an idea that an effect is caused by a specific combination of multiple factors that have to come together rather than by individual independent variables.

Example 3: causal processes in agent-based models

Process theory, as a form of causal explanation, is rooted in a realist approach to causation (Maxwell, 2004). Conducting an in-depth study of one or few cases, engaging with a small sample of individuals, or examining qualitative secondary data (e.g. documents, movies, photographs), researchers are able to recreate chronological and contextual connections between events (i.e. causes and effects). Antosz et al. (2020) implemented the approach to the phenomenon of shirking – voluntarily working less than expected by the superior in an organization. After a failed approach to ground the agent-based model in game theory (Antosz & Verhagen, 2020), the authors turned to qualitative, processual approaches for help. A review of the literature provided a picture of factors that play a role in the amount of employee shirking. However, the question of: *how does shirking actually happen?* remained open. To fill in the gaps about the general structure of the work process individual in-depth interviews with employees and managers were carried out. Qualitative information drew attention to processes that have not yet been described in the literature: the crucial role of (1) managerial expectations, against which employee performance is measured, and (2) unexpected events that might either cause delays or speed up the task execution. Acquired information allowed for defining agent types with their role-specific actions, and served as guidance for model scheduling: starting with creating tasks of various complexity, these tasks are further allocated to employees according to manager's imperfect knowledge about employees and tasks, in the last step employees complete the tasks and inform the managers. Moreover, information provided clear rules for role-specific actions. For example, managers only allocated tasks to available employees, and task difficulty corresponded with employee competence (both as perceived by the manager). Last but not least, processes that respondents described allowed for identifying a crucial parameter that differentiates between various occupations: the proneness to reality flukes – unexpected misestimations of true task difficulty. Many more examples of combining causal processes with agent-based modelling can be found in the companion modelling approach (ComMod) influenced by the French teams of Barreteau, Le Page, Bousquet, and colleagues (Barreteau et al., 2014).

Conclusions

We argue that agent-based modelling is an integrative platform for various types of causal relationships, as they are depicted by a given researcher. This extraordinary capacity to work with other methods is crucial when tackling the complex problems of the modern world. As representatives of generative social science and builders of agent-based models that explain macro-level social phenomena, we strongly believe that any feasible explanation of such phenomena cannot overstate the importance of the micro-level interactions through which the macro-level emerges. Explanations that actively ignore the interactions among individuals embedded in social networks or that deny these interactions matter, are in our view incomplete. However, in constructing our mechanistic, generative explanations we admit that not all causal relationships are multilevel, and even if a phenomenon can be seen as generated by interacting entities on a lower level, it is not necessary to always represent it as such. ABMs are capable of mirroring the crucial, multi-level component of emergent phenomena, while not limiting the scope of the offered explanation and recognizing the important role of single-level causal forces. Implementing various types of causal relationships to *complement* the generative causation offers insight about *how* a multi-level phenomenon happens and allows for building more complete causal explanations.

The causal relationships executed in an ABM can originally be expressed in various symbolic systems: in both human and computer languages, including various forms of scientific notation, singular linear and non-linear equations, systems of equations (e.g. present in multi-level or structural equation modelling) and natural languages. Graphical expressions e.g. in the form of UML diagrams (Siebers & Davidson, 2015) or even theory of change diagrams (Wilkinson et al., 2021), can also be successfully used as ABM input. Challenges to translating the *original* language into ABM code may relate to assuring the modeller has sufficient insight into the original causal statement, especially if those statements are not expressed in scientific notation that can be straightforwardly implemented as model code. Therefore, in complex models it is crucial to cooperate with subject matter experts and take adequate time to guarantee not only the understanding of causal relationships going into the model, but also the consequences of the way those relationships were translated into the target ABM language. Besides that, any limitation for AMBs to include all relevant causal relationships and/or precisely quantify them is empirical and stems from challenges inherent to data collection and analytical techniques, rather than from the nature of an ABM *per se* and would equally apply to other modelling (and non-modelling) analyses.

Last, we tackle the micro-chauvinistic myth. Agent-based modelling is not committed *exclusively* to emergence, even though this type of causal mechanism is its distinctive characteristic emphasized by the Santa Fe Institute pioneers and vocal proponents who wanted to establish its methodological identity and differentiate it from other computational methods. As a stand-alone methodology, it is fully capable of representing bi-directional, multi-level causal relationships and single-level simple and complex causal inferences. Therefore, ABM immanently embraces various approaches to causality. Even though the macro-level outcome is indeed generative, experimenting in simulations follows a probabilistic, counterfactual approach (controlling for confounders by keeping multiple factors constant) and sensitivity analysis may follow a multiple conjunctural approach, looking for combinations of factors that impact the outcome of the model.

Notes

1. We thank Reviewer 3 for pointing out that multiple approaches to social mechanisms exist, including ones that are not micro-chauvinistic, incl. Bunge (2004) or Mayntz (2003).
2. The reflections on multi-level phenomena in section 2 are focused on two-level models i.e. micro and macro. In reality, ABMs are capable of representing more complex systems with multiple, partially-interacting layers of structure (Gimona & Polhill, 2011). Therefore, the interpretation of this section should not be limited to two level-models only.
3. The view has recently been contested, see, (Lange, 2017; Reutlinger & Saatsi, 2018).
4. For a review and critique of mechanistic theories, see, Williamson (2011).
5. In Machamer et al.'s (2000) version, complex-systems theory is a generalization of process theory.
6. For a broader discussion on types of emergence, see, Bedau (2002).
7. We thank Reviewer 2 for a thoughtful comment on the matter that challenged our initial thinking. Note that we follow a broad, functional definition of a research design: *The function of a research design is to ensure that the evidence obtained enables us to answer the initial question as unambiguously as possible* (De Vaus, 2001, p. 9).
8. For an alternative typology, see, Szostak (2015).
9. For other philosophical theories of probabilistic causality see, also Reichenbach (1956), Good (1961-1962), and Suppes (1970).
10. For a discussion on the controversial topic of causal explanation in qualitative methods, see, Maxwell (2004).
11. Or, perhaps, all the causal assumptions they know how to handle? – see, Edmonds (2015) on the use of qualitative data in ABM.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Patrycja Antosz is a sociologist and a psychologist whose research has focused on three areas: (1) social simulation of complex systems, (2) work and organization studies, and (3) public policy analysis. Having used agent-based modelling for over a decade, she specializes in applying the methodology in a mixed-method designs alongside qualitative and quantitative techniques. Patrycja is an active member of the scientific community, currently serving a second term in the European Social Simulation Association's Management Committee, and a firm believer in using science to support evidence-based policy making.

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Paper 2

GAM on! Six ways to explore social complexity by combining games and agent-based models.

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GAM on! Six ways to explore social complexity by combining games and agent-based models

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ABSTRACT

GAM, combining games and agent-based models, shows potential for investigating complex social phenomena. Games offer engaging environments generating insights into social dynamics, perceptions, and behaviours, while agent-based models support the analysis of complexity. Games and agent-based models share the important ability both to input and output qualitative and quantitative data. Currently, there is no overview of GAM approaches. In a systematic literature review, we identified six research design types in empirical studies to date. The functional range of these design types is wide, with diverse application domains involving analogue, digital, and hybrid games. This makes GAM a highly versatile approach, appealing to researchers in both natural and social sciences, along with the gaming community itself. To consolidate the GAM field, we propose recording the design and implementation of studies that combine games and agent-based models by using a dedicated documentation scheme.

KEYWORDS

Agent-based modelling; games; game design; research design; systematic literature review

1 Introduction

The gaming sector has grown to enormous size. With estimates of about 2.4 billion active gamers worldwide (Clement, 2021), approximately one-third of the human population is playing regularly. The potential of games to create engaging environments where people interact, explore, and take on collective challenges is well known (Ampatzidou & Gugerell, 2019). "Computer-assisted gaming has moved into social studies, urban and land-use management, ecology education, international relations, healthcare, and natural resources" (Klabbers, 2006), often to support public participation or to communicate research findings to wider audiences (Pfirman et al., 2021). In recent years, we have observed the rising popularity of research applications combining games and approaches used to explore social complexity, such as agent-based models (ABMs). Today, we find manifestations of these combinations in hybrid composite simulation (Le Page et al., 2014), agent-based participatory simulation (Guyot & Honiden, 2006), or experimental setups

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(Ren et al., 2018). However, the consolidation of the emerging field combining games and agent-based models, which we propose to call GAM, is hindered by the absence of methodological advice about how and when to use this combination, slowing down its uptake, replicability, and systematisation. First-time practitioners are particularly affected by this issue because they cannot rely on intuitions and tacit knowledge available to their more experienced colleagues who often pioneered the field. This lack of systematic methodological description leads to local innovations and reinvention of research designs. This article aims to lay a methodological foundation for GAM by developing a structured overview and analysis of existing practices (how and when the GAM has been used) and by proposing a documentation scheme to maintain consolidation. This can serve as a first basis for future methodological debates. In particular, the study a) identifies general patterns in GAM papers (e.g. frequency of publication over time, application domain, publication outlet, authorship), b) synthesises existing research design types used to combine game and ABM applications, c) describes application areas of such design types (over time, purpose, field, and collaboration practices), and d) proposes a structure to document research studies using GAM. In order to make the GAM methodology explicit, we characterised each research design type by four features: (1) sequencing of research elements, (2) correspondence between elements, (3) relationship with the real-world phenomenon under investigation (target system), and (4) purpose of combining the two elements. Thus, this article will inform and inspire both novices and experienced researchers in choosing context-appropriate designs for applied research and improving current practice. The study targets practitioners in gaming and social simulation communities by providing evidence, insight, and guidance on how to combine the two approaches effectively. Consequently, results presented here are also of value to practitioners interested in integrating qualitative and quantitative evidence (which is a strength of both games and ABM). While the study reviews research applications, combinations of games and ABM can also be used for other purposes, mainly learn-based interventions to trigger and facilitate change (e.g. Rodela et al., 2019).

This paper continues with a description of games and ABMs, highlighting the benefits of combining them. Subsequently, we outline the criteria developed to describe the diverse research designs implemented in past empirical studies. Methodology and limitations of our review are reported in Section 3, followed by the results in Section 4, focusing on the research design types identified. Recommendations for using and reporting the GAM approach are then presented in Section 5. The article closes with a summary and suggestions for future development.

2 Conceptual background

2.1 Games and ABMs

Defining what a game is in general terms is not an easy task. Various attempts highlight specific characteristics of games. Some authors point out that a game is fun or at least entertaining (Caillois, 2001), while others define it as a system in which players engage in an artificial conflict (Salen & Zimmerman, 2003). In this study, we follow an inclusive definition of games formulated by game designer McGonigal (2011, p. 21), offering analytical advantages: 'When you strip away the genre differences and the technological complexities, all games share four defining traits: a goal, rules, a feedback system, and voluntary participation.'

Some unique traits of games are particularly interesting for researchers. For example, games can provide an imaginary setting in which players take on particular roles in a defined situation (Barreteau, 2003). The imaginary settings of games allow players to explore, cooperate, or compete without experiencing real-life consequences. The act of playing a game can be interpreted as a mode of communication in which players use a rule-based language to transmit and receive messages (Duke, 1974). In science, games have been used to support social learning, communication, collective decision-making and increase the overall engagement of stakeholders in participatory approaches (Bakhanova et al., 2020). Additionally, games are used as data collection tools, successfully engaging volunteers in citizen science projects (e.g. www.fold.it).

ABMs are abstract representations of complex systems depicted from the perspective of their components and inter-relationships instantiated as computer programmes. In an ABM, heterogeneous agents characterised by multiple attributes interact with one another and the environment based on a defined set of formal rules (Miller & Page, 2009). By analysing the outputs of the programme, emergent macro-level phenomena can be rigorously related to the individual characteristics and behaviours of the implemented software agents. Importantly, agent-based modelling allows researchers to systematically explore counterfactual scenarios in an in silico environment.

In combining a game with an ABM in a single research application (i.e. using a GAM approach), researchers can benefit from both their individual strengths and the synergy between them. This potential was initially employed in the field of natural resource management. The idea of combining games with ABMs was first described by Barreteau (1998) and Bousquet et al. (1999) to support integrated management approaches. Barreteau et al. (2002) pointed out that there is a striking correspondence between the features of an ABM and those of a game: agents and players, model rules and game rules, model time steps and game turns, simulation runs and game sessions, a model interface and a gameworld and so on. In a GAM setting, the ABM offers opportunities to (1) create counterfactual what-if scenarios, e.g. by digitally replaying the gaming sessions with altered parameters or attributes, (2) scale up gaming sessions, e.g. by expanding spatial and temporal dimensions, (3) continuously update the characteristics of the environment and agents to react to player actions as the game unfolds, and (4) provide generative properties (i.e. population level phenomena originating from local interactions) and the ability to model dynamics. In the same context, games can provide a platform for players (e.g. stakeholders) to discuss and agree how best to manage real-life challenges (Salvini et al., 2016), or collectively create development scenarios (Voinov & Bousquet, 2010). Moreover, they can help understand heterogeneous behavioural strategies and interactions among players. This particular strength can be used either to develop plausible context-specific behavioural ABMs, or for validation purposes (e.g. by comparing the behaviours of players in the game with those of the computational agents). A significant trait of both games and ABMs is that they can input and output qualitative as well as quantitative data. Depending on the research design sequence, data can feed from the game to the ABM or vice versa.

Previous research examined games and ABMs applications in a participatory context (Voinov & Bousquet, 2010; Voinov et al., 2018, 2016). In these three studies, games are limited to role-playing games (RPGs) with stakeholders and fall into one of two types: (1) companion modelling, which is usually associated with a stakeholder process that involves a combination of ABMs and RPGs with the aim of co-designing a system model or (2) participatory simulation, in which stakeholders manipulate a dynamic system in the context of a game where every decision and each interaction is registered for further analyses, while the settings and the rules of the underlying model cannot be modified by the players. In a systematic literature review, Farias et al. (2019) identified four ways to integrate combinations of multiagent systems (MAS) and RPGs in natural resource management: (1) RPG -> MAS, where the analogue RPG is used to collect information about a problem and how the stakeholders take their decisions – this information is used to make a MAS; (2) MAS -> RPG, where the MAS is developed prior to playing an analogue RPG, and it is validated via running the RPG; (3) RPG + MAS, where an analogue RPG uses a MAS to calculate game processes; (4) RPG ++ MAS, where a computational RPG is developed as software that integrates MAS calculations. The presented results are significant but limited in their applicability because of the small dataset and limited scope of the review. Our study tries to overcome these limitations by analysing an extensive dataset rooted in the entire disciplinary spectrum of GAM applications.

2.2 Criteria for describing games and ABMs research designs

In order to identify and categorise research designs used in GAM, we determined three criteria that we then applied in this study: sequencing, target system, and game/ABM correspondence. We borrowed the first and the third criteria from mixed methods research (Cresswell & Clark, 2017). The second criterion was chosen because it sets the boundaries of the ABM and of the game model.

- **Sequencing** refers to the relationship between research components over time (Morgan, 2017). In our case, a sequence describes the order in which game and ABM components are designed (and sometimes implemented) in a particular study. The sequence influences the flow of information between elements, usually from the first to the second. Analysing sequencing, games and ABMs can be combined in three ways: a game is followed by an ABM, a game follows an ABM, and the two can be merged in a single application.
- The **target system** describes the real-world phenomenon under investigation (Elliott-Graves, 2020). Both games and ABMs are designed as simplified models of the studied phenomenon, where researchers highlight elements significant for a specific question and heavily simplify and/or disregard other features. Therefore, we analyse to what extent the game and the ABM highlight the same aspects of the phenomenon investigated.
- **Game/ABM correspondence** indicates whether the latter component in the research design depends on processes present in the earlier component (Schoonenboom & Johnson, 2017). It can also be the case that the two components are completely or partially inseparable.

3 Method

In order to address our research questions, we employed a systematic literature review (SLR), which is a structured way to gather, review, and analyse relevant texts, followed by content analysis. In emerging fields, SLRs can reveal consistencies in practice, provide a structure for these, and identify areas needing further organisation. At a later stage, an SLR can be repeated to re-evaluate findings and observe long-term developments in the field. SLRs have been used in a variety of domains with the purpose to assess developments, including natural resource management (Weber et al., 2019), business (González et al., 2010), software engineering (Šmite et al., 2010), and social simulation (Farias et al., 2019; Gu & Blackmore, 2015). In this study, we followed the SLR phases described in (Bearman et al., 2012) and the content analysis methodology as described in (Krippendorff, 2012). Figure 1 summarises the steps that were taken during the SLR.

Available metadata such as article's author(s), publication year, abstract, journal, keywords, and publication outlet were collected and served as the basis of the screening process, in which eight of this article's co-authors assessed all articles with respect to relevance and eventually included or excluded them from the review. Articles where inclusion was uncertain (based on the screening of title, keywords, and abstract) underwent additional full-text assessment by two co-authors. To control for inclusion consistency between reviewers, two co-authors cross-checked all final decisions for 5% of randomly selected papers. The list of items that were selected for in-depth analysis can be found in Appendix A, Table A1.

The abstracts and full texts of items selected for investigation were then subjected to content analysis. Qualitative coding was used to identify patterns in the ways games and ABMs were combined. The codebook was developed and tested using a combination of deductive and inductive coding. After finalising the codebook, the co-authors harmonised their coding practices through three iterations. After reaching satisfactory reliability, we analysed the entire qualitative dataset using NVivo. Figures were made using SPSS 26.0.0.0. After coding, we used the categorisation criteria described in Section 2.2 main text to identify recurring research design types.

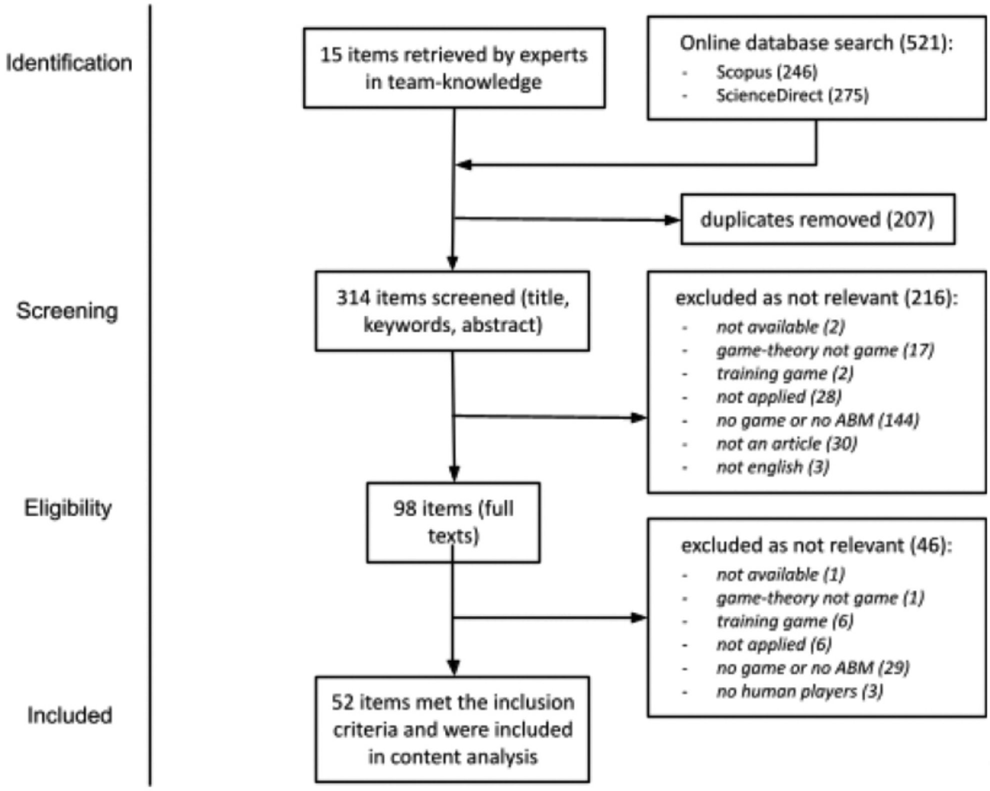


Figure 1. Flow of information through the different phases of the systematic literature review. Search date: 25.02.2020.

In order to identify authorship patterns, we identified a study field matching affiliation of the author with the scientific fields descriptors from Marie Skłodowska-Curie Actions – List of Descriptors (European Commission, n.d.). We have also counted the number of authors per article, categorised authors as belonging to academic or non-academic domains, and assigned a geographical location based on affiliation.

The main limitations of the SLR approach are the literature selection process and the population of publications used for analysis. Articles that are not stored in one of the two online databases or do not include our search terms are excluded from the review (Table 1). This means that it is possible that important articles escaped our review. However, this is always a price that must be paid for 'automated' search of a much larger sample relative to 'qualitative' analysis of articles following up references. We did not include any articles after the database search was concluded (on 25.02.2021).

Table 1. Search strategy of the systematic literature review performed for this study.

Data sources	*Expert knowledge*: selected articles known to team members. *Databases*: selected articles after an initial investigation into the quantity and quality of the search results and into the accessibility of an application programming interface to the research team: Scopus: www.scopus.com ScienceDirect: www.sciencedirect.com
Search terms	TITLE-ABS-KEY((*'gaming' OR "role playing game OR 'serious game' OR 'board game' OR 'online game' OR 'computer game'*) AND (*'agent based model' OR 'agent based simulation' OR 'individual based model' OR 'individual based simulation'*))
Inclusion criteria	Article in English. Published in a peer-reviewed journal, proceedings, or book. Application in research domain. A game and an agent-based model were included (though they could be the same).

All our findings refer to the sample used for the analysis and therefore have finite generalisability. Although it is a limitation of the study that subjective interpretation of criteria may have affected this categorisation, this is the first systematic attempt and is therefore subject to evaluation and further improvements.

4 Results and discussion

4.1 General patterns

Combining games with ABMs for the purpose of research (i.e. using the GAM approach) is a relatively new field. The 52 analysed papers were published between 2001 and 2020 (Figure 2). The GAM approach is mainly published in three journals: Environmental Modelling & Software (n = 6), Journal of Artificial Societies and Social Simulation (n = 6), and Journal of Environmental Management (n = 5). The remaining 35 papers were published in 35 different outlets (16 conference proceedings, 12 peer-reviewed journals, 7 books or book series). Almost one-third of the papers were published as conference proceedings from computer science-oriented conferences. The variety of publication outlets shows that the relatively low number of GAM research projects are wide-spread over different application areas, which paints the image of a scattered field. However, eleven publications in this review are from journals that focus on environmental management, high-lighting the significance of the approach when working with cross-sectoral complex problems.

The practice of combining games and ABMs has been growing in popularity (Figure 2). While in our sample the first decade under investigation (2001–2010) produced a total of 14 papers on the topic, in the subsequent one (2011–2020) publications increased almost threefold (38 papers). The 2010 peak is traceable to a series of publications in Environmental Modelling and Software, driven by an author group publishing on companion modelling, while the slight downward trend in 2019 and 2020 is most likely an artefact of our data collection that took place in February 2020.

The combination of games and ABMs was applied in 14 different fields, showing a high degree of flexibility. The most prominent application domain is natural resource management (54%), fol-lowed by group dynamics (14%), public health (6%), and city logistics (4%). This pattern might also reflect the popularity of ABMs in environmental, agricultural, and biological sciences in general (Figure D1), most probably due to the complexity approach being popularised in these domains in the last 30 years calling for application of mixed methods.

Almost half (48%) of the studies used computer-based games, a third (31%) used analogue games, and a fifth (21%) used games that combined physical and digital elements. The popularity of computer games can be attributed to several factors. They are easy to set up and efficient for tracking data; furthermore, an online game makes a study independent of the location because it offers players the possibility to participate from anywhere. Almost all the analogue games were

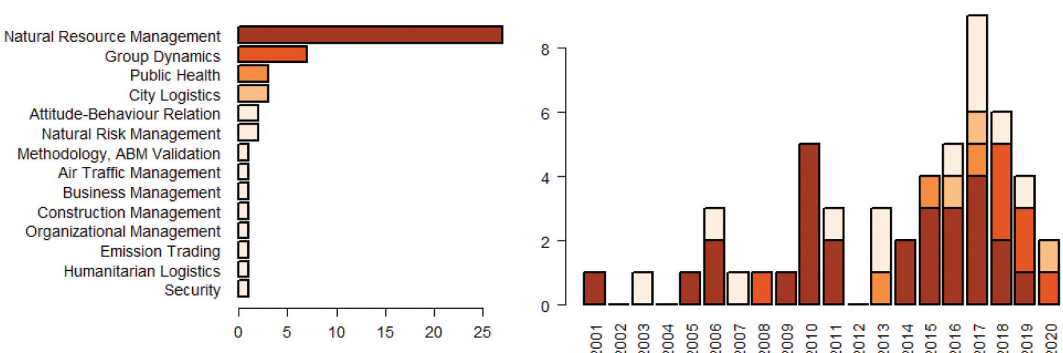


Figure 2. Distribution of publications over time and application domain.

RPGs. The prevalence of this category of games might be due to the underlying assumption that RPGs can be seen as ABMs that use humans instead of artificial agents. Only in one case (Table A1, #44), a commercial off-the-shelf game was used. The remaining studies used games made for the research purpose or employed games designed or used in previous research applications.

The structure of authorships shows that there are no 'lone wolves' among the authors and that the field is dominated by small-to-medium collaborations, as 70% of publications are authored by two to four scholars. The largest collaboration included 19 authors.

Most of the collaborations are international (67%) and established between universities and non-academic institutions (57%). Non-academic institutions are mostly research institutes and private companies, but sporadically also government agencies and hospitals. This reflects the transdisciplinary potential of the GAM approach, with cooperation between scientists, stakeholders, and experts from the (often rural and remote) field.

Moreover, the authors of the studies included in our dataset have a plurality of research backgrounds. The affiliation of the majority of authors matched 'Environmental and Geosciences' (40%), a highly multi- and interdisciplinary domain, and 'Information Science and Engineering' (39%), a domain where computer models and games are well-known, with significantly fewer authors being affiliated with 'Social sciences and Humanities' (8%), 'Economic Sciences' (4.5%), 'Life Sciences' (4.5%), 'Physics' (2.3%), 'Mathematics' (1%), and 'Chemistry' (0.5%).

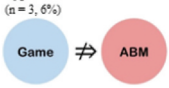
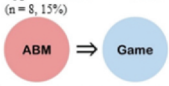
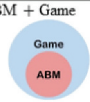
We found two types of collaborations: (1) field studies where specialists cooperate with practitioners in the field, oftentimes in international cooperations between research institutions and non-research organisations and (2) studies organised around research institutions where cooperating researchers come from different scientific backgrounds. Thus, the complexity of applying games and ABMs in a single research design seems to stimulate collaborations. However, exact reasons for establishing cooperative efforts were not provided in the analysed papers. It might be difficult for a single scholar to have the knowledge and expertise related to all study components, e.g. the methodology and the application field or the methodology and the location of the case study. It is also possible that the complex organisation and execution of the study simply requires the participation of multiple scholars.

4.2 Research design types: description and patterns

When applying the three criteria (described in Section 2.2) on the 52 papers included in the content analysis phase of the SLR, we identified six types of research designs. These types are visualised and their characteristics are summarized in Table 2. An in-depth description of the data that made up each of these types is given in Appendix B. The research design types have some similarities with those described by Farias et al. (2019) in an SLR that included 10 papers from natural resource management that had used multi-agent systems (MASs) and RPGs. The previous study used sequencing and level of RPG computerization as characterisation criteria. Our types 1, 3, and 5 are similar with their integration ways a, b, and c with respect to sequencing. Our study differentiates three more types: types 2 and 4, because of using the target system as a characterization criterion (inspired by the category shared or different underlying conceptual model in the analysis of the joint use of role-playing games and models in Barreteau (2003); and type 6, because of the simultaneous sequence. Farias et al. (2019) differentiates integration way d because of the level of computerization of the game as a characterization criterion, something that our study does not regard.

The GAM field is not only increasing in the number of publications but also in variations of applied research design types (see Figure D2). Types 3, 5 and 6 are present in the first third of the observation period, while the other three types appear later on. The first appearance of type 1 studies was in 2010, with four publications in 1 year. Since then, it has slowly faded out with no new publication for the last 4 years. Type 3 studies are distributed over the whole observation period, with a slight increase in the fourth quarter. Since both types (1 and 3) can be used for similar research purposes, one should also review them in relation. This combined perspective shows a

Table 2. Description of the six research design types combining games and ABMs identified by this systematic literature review.

Type	Game/ABM sequencing	Target system	Game/ABM correspondence	Purpose and application
Type 1: Game => ABM (n = 9, 17%) 	*from game to ABM*	*identical*	*the ABM design is influenced by the processes and scheduling of the game*	*Suitable to promote communication, mutual understanding or learning among stakeholders and scientists. Aims to understand a group of stakeholders on the collective level. Most used:* *- stakeholder involvement* *- citizen science*
Type 2: Game ≠> ABM (n = 3, 6%) 	*from game to ABM*	*different*	*ABM is independent from game processes and scheduling; results from the ABM might influence the further development of the game*	*Aims to understand or analyse decisions or interactions in a game through the application of an ABM.* *Most used:* *- improve game performance & calibration*
Type 3: ABM => Game (n = 8, 15%) 	*from ABM to game*	*identical*	*the game design is influenced by the processes and scheduling of the ABM*	*Suitable to gather additional knowledge. Aims to verify, validate or calibrate the simulation.* *Most used:* *- community-based science* *- stakeholder involvement*
Type 4: ABM ≠> Game (n = 9, 17%) 	*from ABM to game*	*different*	*the game design is independent from the processes and scheduling of the ABM; results from the game might influence the further development of the ABM*	*Aims to use games to investigate questions revealed by the construction and analysis of the ABM that were not obvious when making the ABM. Aims to discover knowledge/answers posed by the ABM and its analysis.* *Most used:* *- research human behaviour*
Type 5: ABM + Game (n = 6, 12%) 	*simultaneously*	*identical or different*	*the ABM is part of the game*	*The ABM implements a (sub-)component of the game.* *Most used:* *- stakeholder involvement*
Type 6: ABM = Game (n = 17, 33%) 	*simultaneously*	*identical*	*ABM and game are intertwined in one application (AB-game)*	*The ABM provides the infrastructure for game interaction and play.* *Most used:* *- stakeholder involvement* *- business games / simulation games*

n = number of articles with corresponding research type.

constant distribution with peaks in 2010 and 2015. Although type 6 is an early occurrence in our dataset, it became the most popular design type only in the second period. Type 4 studies constitute a recent development in the field. The rising popularity of types 4 and 6 can be attributed to the increase in popularity of (video) games and the increased availability of user-friendly development platforms.

While the combination of games and ABMs was applied across many different fields, the research design types were not equally distributed (see Figure D3). Almost all research design types (except type 2) are used in natural resource management. Type 6 seems to be the most versatile, being used in 10 out of 14 application domains. Research design type 1 finds applications solely in natural resource management, while all the other types are present in at least two out of 14 application domains. Type 2 is used exclusively in the two application domains concerned solely with human social behaviour (group dynamics, attitude behaviour relation) as opposed to the socio-ecological or socio-technical systems under investigation in the other domains. This is probably because using a game to elicit knowledge about people's decision-making and attitudes and then validating these findings via an ABM seems to be especially suitable for studies in these fields.

5 Recommendations for future developments

5.1 General aspects

Drawing on the studies included in this SLR, we give brief implementation guidance for using each of the research design types and a description of the limitations of the GAM approach. The recommendations provide (especially new) researchers with a helping hand to identify an appropriate design type for their research purpose. These recommendations are useful to ABM developers and game designers alike. We also invite academics and practitioner-researchers to join a methodological discussion and critically reflect on the GAM research design types and provide robust advice in relation to shaping the GAM methodology.

Type 1 (Game ⇒ ABM) research design is suited for studies that aim to gather insider and local knowledge to widen the understanding about a specific target system. The purpose is to support decision-making processes by involving stakeholders in the co-construction of an abstract representation of a real-world system, i.e. the concept model. The game is used to support the design process of the subsequent ABM. It is employed to create a concept model of the system under investigation through play-testing and debating of the system elements. This concept model outlines the system under investigation and will, at a later stage, be used as the blueprint for the ABM. The ABM component is then used to present and discuss development scenarios.

Type 2 (Game ⇏ ABM) research design is well equipped to support game development. The aim of a type 2 design is to enhance the performance or calibration of game aspects by utilizing ABM. This design is also suitable when recreating a scalable version of the game *in silico* to explore social patterns and dynamics of players. Type 2 designs aim to use an ABM to understand/analyse the decisions and interactions in the game and sometimes evaluate and compare different theories on cooperation, group interactions, collective decision-making, etc.

Type 3 (ABM ⇒ Game) research design has the same aim and purpose as type 1 research designs, i.e. gathering player knowledge. Hence, the game is used to co-design and discuss system concepts through play-testing and debating its elements in a concept model. Uniquely for type 3 designs, the study is initiated with an ABM and subsequently a game is created to mirror the basic concepts of the ABM. This sequence allows for model validation to improve or undergird an existing ABM with knowledge gathered through the game. Type 3 designs aim to verify, validate or calibrate the simulation.

Type 4 (ABM ⇏ Game) research design aims to enrich ABMs with more realistic agent behaviours or to compare implemented agents to real humans. In this design, games are utilized in controlled settings (e.g. experiments) to track behaviour of players during gameplay. On the basis of the gathered data, new agent behaviours are then created or existing agent behaviours are validated. Type 4 designs aim to use games to investigate questions revealed by the construction and analysis of the ABM.

Type 5 (Game + ABM) research design use ABMs to calculate and present the effect of players' actions on the gameworld during the gameplay, e.g. to demonstrate the effects of players' decisions and actions on the environment parameters such as groundwater level, land production, government budget, etc. Therefore, at each game-turn, the gameworld parameters get updated based on the ABM processes, and new values are presented to the players. As such, the game will not be able to run without the ABM and its results. Type 5 designs aim to implement ABM as a (sub-) component of the game.

Type 6 (ABM = Game) research designs combine an ABM and a game in one fully integrated application, i.e. agent-based game. This approach is particularly suitable for decision support tools, but studies utilizing the design can also be used for all previously mentioned study purposes. The integration of game and ABM comes with strong ups- but also downsides. On the one hand, using this type of research design makes data integration between the game and ABM obsolete. On the other hand, this design limits the possibilities of players to show unexpected gameplay, e.g. by modifying the game rules or implementing 'house rules'. Type 6 designs aim to use an ABM to provide the infrastructure for game interaction and play.

When considering using any of these research design types, one has also to be aware of the limitations of the GAM approach. Implementing this approach requires a double set of design and implementation skills, i.e. for games and for ABM. In addition, one has to have the knowledge of combining the two in an effective way. To the authors' knowledge, with the exception of this current study, there is only one overview of general methodological approaches in combining games and ABMs (i.e. the analysis of six cases by the initiators of the companion modelling approach by

Bousquet et al., 2002). Implementing a GAM study is a time and labour-intensive process. Therefore, it is recommended to plan well in advance both the time needed to acquire the necessary skills and the time to implement the combination of games and ABMs.

Interestingly, papers included in the review frequently lack a clarification of basic concepts, e.g. a study purpose or research questions. Moreover, explanations of the reasons behind design choices and how they are translated into a specific combination of games and ABMs are non-existent or unstructured. Consequently, it is unclear if a GAM research design is fit for purpose. Therefore, the classification of some studies was generally challenging because the texts did not include sufficient details or explicit descriptions for identifying a clear sequence, distinguishing between the target systems, or describing the game/ABM correspondence. We also realized that the uneven distribution between sections documenting the game and the ABM components of GAM is because, while there is a call for rigour in game modelling (Raghothama & Meijer, 2018), there are no schemes for game documentation. There are, however, several protocols available for reporting ABM (e.g. Overview Design concepts and Details Protocol (Grimm et al., 2020), Rigor and Transparency Reporting Scheme (Siebers et al., 2021)).

5.2 Games and agent-based models (GAM) documentation scheme

To facilitate writing and reading of research methods descriptions, enable replication of GAM research, and further the field through structuring it and using a GAM-specific vocabulary, we recommend practitioners to use a simple documentation scheme, as outlined here. It should be noted that this is just a first attempt to design such a scheme and requires further study and validation in future. We welcome feedback on the content, use, and usefulness of this scheme (printable version in Appendix C).

A) General aspects:

(1) Purpose of the study. [open ended]
(2) Research questions of the study. [open ended]
(3) Application field. [open ended]
(4) Type of GAM. [1.Game – > ABM, 2.Game -/-> ABM, 3. ABM – > Game, 4. ABM -/-> Game, 5. Game + ABM, 6.ABM = Game]
(5) Additional comments. [open ended]

B) GAM:

(1) Purpose of using the GAM methodology. [open ended]
(2) What is the GAM design (e.g. sequences, phases, procedures, iterations, information flow)? [open ended]
(3) How are the game and ABM linked (e.g. specific information from gameplay that was used to validate the ABM, how was the gameplay data used to inform ABM rules, how ABM simulations are used in the game)? [open ended]
(4) Limitations of the specific GAM implementation. [open ended]
(5) How did using GAM contribute to answering the research questions of the study? [open ended]
(6) Advice for others. [open ended]
(7) Additional comments. [open ended]

C) Game:

(1) Target system. [open ended]

(2) Kind of game. [commercial of the shelf; build for purpose, but not for this study; build for purpose for this study].
(3) Game type. [analogue; computer-based; mixed]
(4) Game category:
  (a) Dice and Luck: dice games, start-goal-games, search and catch games
  (b) Layout games: letter layout games, lottery games, figure layout games, picture layout games
  (c) Thinking games: strategic games, tactical games, combination games, memory games, solitary games
  (d) Quiz-/Communication games: question & answer games, quiz games, fortune-telling games, creativity games
  (e) Role-play games and simulations: economy games, criminal games, adventure games, conflict games
  (f) Dexterity games: dexterity games, action games, reaction games, sport games
  (g) Other: ________________.
(5) Who are the players (e.g. stakeholders, students, fellow researchers, general public)? [open ended]
(6) How were the players selected? [open ended]
(7) Game objective. [open ended]
(8) What are the core game mechanics? [open ended]
(9) What data are collected from gameplay? [open ended]
(10) How are the data collected from gameplay (e.g. observation, tracking, etc.)? [open ended]
(11) If debriefing was performed, how was this done? (If debriefing was not performed, give a reason for that decision.) [open ended]]
(12) What data are collected after the gameplay? [open ended]
(13) How are the data collected after the gameplay (e.g. questionnaire, interview, focus group)? [open ended].
(14) What does the game add that would not be known otherwise? [open ended]
(15) Additional comments [open ended].

D) ABM:

(1) Target system. [open ended]
(2) Link to filled in documentation/reporting protocol/scheme: _______________
(3) What does the ABM add that would not be known otherwise? [open ended]
(4) Additional comments. [open ended].

6 Conclusions

Combining games and ABMs shows great potential to become a significant methodology in applied interdisciplinary or transdisciplinary research settings. As the GAM approach profits from the enormous popularity of digital and analogue games and the ability of ABMs to tame complexity, it can be scaled up in three dimensions: (1) Quantity of data: By using online games for data collection, researchers can attract big crowds to participate in the research process. Using games in research also takes advantage of the tendency of humans to spend many hours engaging in games. This allows researchers to collect data from many sources and over an extended period of time. (2) Quality of research: Standardising the GAM methodology will allow researchers from various fields to replicate research designs adequate for specific research settings. Using GAM applications tailored to investigate player behaviour in small groups can lead to a new wave of context-specific insights on human group dynamics and social behaviour. (3) Empowerment of stakeholders: Creating compelling and engaging environments for participants to engage in research processes will increase the impact and sustainability of decision-making processes that build on stakeholder involvement.

Employing a systematic literature review, this study identified six research design types that characterize the GAM approach. This characterization describes the current state of the field and helps to introduce the GAM approach to new research domains. The functional range of these design types is wide, with applications in 15 domains that mainly focus on decision-making and managing complex systems. The six types can accommodate any type of game: analogue, digital, and hybrid. This makes the GAM approach a highly versatile tool. We describe these six types by explaining key concepts of their designs: sequence, correspondence between game and ABM, how they represent target systems, and their purpose. In order to help newcomers in the field, we give advice in what circumstances each design can be used. The six types provide a framework for scientists to communicate their work by relating it to a broader context without the danger of reinventing (re-labelling) existing concepts. The gained transparency and definiteness of the categories set the scope for methodological discussions that can lead to advancements in the field and the documentation of applications. In addition, the overview helps to identify novel research designs that have not been categorized in this review.

To consolidate the GAM field, we propose to keep track of the design and implementation of studies combining games and ABMs by using a dedicated documentation scheme, as suggested here. To further the field, a thorough description of each of the six design types is needed, together with detailed expositions of implementation examples that open the black box of how specific combinations of games and ABMs can integrate qualitative and quantitative data. Increased cooperation between ABM practitioners from any application domain and members of the games community (designers, players, researchers, etc.) is needed in order to achieve the full potential of the GAM approach.

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Paper 3

Quantum Leaper: A Methodology Journey From a Model in NetLogo to a Game in Unity.

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Quantum Leaper: A Methodology Journey From a Model in NetLogo to a Game in Unity

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Abstract Combining Games and Agent-Based Models (ABMs) in a single research design (i.e. GAM design) shows potential for investigating complex past, present, or future social phenomena. Games offer engaging environments that can help generating insights into social dynamics, perceptions, and behaviours, while ABMs support the representation and analysis of complexity. We present here the first attempt to "discipline" the interdisciplinary endeavour of developing a GAM design in which an ABM is transformed into a game, thus the two becoming intertwined in one application. When doing this, we use as a GAM design exemplar the process of developing *Quantum Leaper*, a proof-of-concept video game made in Unity software and based on the NetLogo implementation of the well known "Artificial Anasazi" ABM. This study aims to consolidate the methodology component of the GAM field by proposing the GAM Reflection Framework, a tool that can be used by GAM practitioners, ABM modellers, or game designers looking for methodological guidance with developing an agent-based model that is a game (i.e. an agent-based game).

Keywords Agent-based model · Archaeology · Framework · Game · Game design · Interdisciplinarity · Methodology · Reflection

1 Introduction

GAM, combining Games and Agent-Based Models (ABMs) in a single research design, is a unique way to investigate complex past, present, or future social phenomena. Using GAM, researchers benefit from the individual strengths of Games

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and ABMs and their synergistic effect. Games offer engaging environments to generate insights into social dynamics, perceptions, and behaviours, while ABMs support complexity analysis. The GAM field is relatively new and only a few methodological descriptions are available for those who want to venture into it. A recent Systematic Literature Review of the GAM field [15] provides a general description of six research designs to combine Games and ABMs. The designs are organised in two groups: (1) sequential combinations over time, either from a Game to an ABM or from an ABM to a Game, and (2) simultaneous combinations, where either the ABM provides support to the Game (e.g., to calculate the effect of player actions on their environment) or the ABM and the Game are merged into one integrated application. There is no systematic method description of how to implement this latter design (i.e. GAM type 6 $ABM = GAME$), which leads to practitioners and newcomers in this field still to largely rely on intuition and on *ad hoc* solutions (own creations or imitations). This study contributes to filling up this gap and proposes a way to "discipline" the process of transforming an ABM into a Game (i.e. an agent-based game). This study can be used by GAM practitioners who want to increase the learning value of their practices as well as the rigour and transparency of these. Coordinators of research using GAM designs, ABM modellers or game designers can use this study as guidance to structure the collaborative work in interdisciplinary teams that use these designs.

This study uses *Quantum Leaper* (QL) as an exemplar of GAM type 6 $ABM = GAME$. QL is a proof-of-concept video game made in Unity and based on the NetLogo implementation of the known "Artificial Anasazi" (AA) ABM. Here we present an overview of the QL development, highlighting the main design steps. Starting from these steps we propose a high-level reflection framework that integrates conceptual thinking from interdisciplinarity, ABM development, and game design, i.e. the GAM Reflection Framework. To capture the journey of making this framework, we used a storytelling approach to structure the remainder of this paper in a conclusive narrative.

2 The Settings: The Backdrop and Environment for the Story

The setting is the time and the location in which a story takes place. This setting can be very specific, but can also be more broad. In the case of our story, the setting was a foggy place. We reviewed the literature for general methodological advice about how to develop a GAM design of type 6 $ABM = GAME$, but were not able to find such descriptions. However, we found several individual examples of GAM studies (e.g. [7, 11]). In order to be able to orientate ourselves through the fog, we decided to use an exemplar of GAM study as our focal point and selected the *Quantum Leaper* video game for this role (more details about how this decision was taken are given in Sect. 3). From there on, we looked into studies similar to QL, but found only projects where a 3D game interface was used to visualise and query the output of ABMs depicting historical populations (e.g. [3, 16]). After coming to this understanding, the nature of the settings of our story came clearly in sight: we were exploring an uncharted domain, but we had a starting point.

3 The Characters: Their Role and Purpose

A story usually includes a number of characters, each with a different role and purpose, and there is almost always a protagonist and an antagonist or obstacle to overcome. In our story, there were four protagonists, each with their unique set of tools. Some of these tools can be seen as characters on their own right, having the role of deuteragonist, i.e. the constant companion to the protagonist during the journey. The interest in agent-based modelling and games was a common characteristic of the four protagonists. Otherwise, two of these were digital archaeologists and the other two were active in the natural resource management field. The latter were on a quest of disentangling the methodological intricacies of using games and ABMs as a research device for sustainable resource management when they came across the *Quantum Leaper*. Interested in connecting with the social simulation community, the QL designers joined the quest.

While the antagonist in this story is the difficulty of the disentangling process, the constant companions to the protagonists during their journey were the QL and the "Artificial Anasazi" ABM. QL was used as an (almost) ideal specimen of GAM design type 6 (i.e. an exemplar), as it clearly displayed an agent-based game: an ABM, a game, and the interconnection between the two. The possibility of directly working with its designers had the potential of making explicit the implicit decision-making processes of creating this agent-based game.

Quantum Leaper. QL, a side-project of two of the co-authors of this study, was initiated in 2017 and it was conceptualised as an experiment to embed ABMs into immersive video games, particularly considering the potential of such integrated approach for archaeology. It aimed to demonstrate that 'playing' ABMs immersively can reveal new insights about both the model and the system represented. Even though unfinished, QL was presented publicly on several occasions [2], raising the interest of a wide and diverse public, ranging from archaeologists to game designers. QL is based on the NetLogo implementation of the known "Artificial Anasazi" ABM. For more details, see the part of the development files in [1] and Chap. 5 in [6].

The "Artificial Anasazi" (AA) ABM. AA received great attention because of its implications for the socio-ecological resilience in front of climate change. It represents the population dynamics in the Long House Valley in Arizona (USA), between 800 and 1350 AD [4]. Archaeological data shows that the valley was abandoned towards the end of this period and the main hypothesis put forward pointed to climate change as the main cause. To address this and other hypotheses, the model relates a population of households with a simplified maize-based food economy, dependent on soil types and changing humidity conditions. Simulations are evaluated in reference to the historical estimations of population size and distribution per year. The original authors interpreted the results as indicative that climate change alone was not sufficient to explain the abandonment of the valley. The model was first implemented in Ascape, which is now virtually inaccessible, but was later implemented in NetLogo [19] and published in two quasi-equivalent versions: Janssen's [9, 10] and NetLogo Model Library's [14].

4 The Journey: The Travel From an ABM to a Game

The QL project was organised into three work packages whose tasks intertwined: (A) ABM replication, adaptation, and extension, (B) Game conceptual design, and (C) Game development.

A. ABM replication, adaptation, and extension
Both versions of AA (implemented in NetLogo 5.3.1) were reviewed and translated to C#, the primary language used for scripting in Unity, a popular cross-platform game engine. The alternative of running NetLogo from a C# script in Unity was considered, but discarded due to its technical complexity and potential licensing issues (i.e., releasing a copy of NetLogo together with the game). Bringing AA to C# and Unity involved these tasks.

A1. Creation of a C# library for ABM. C# is a general-purpose, object-oriented language (i.e., not specialised in ABMs). It has little resemblance to NetLogo's syntax, lacking most of its key primitives (e.g., the `ask` command). Thus, the first, and necessary, step in translating the model was the creation of a C# library implementing those NetLogo built-in features used in AA.

A2. Code revision and modification in NetLogo. Code reviewing was guided and complemented with related publications scattered over the last thirty years, including the work done more recently in expanding the original model. By studying the model in detail and translating the NetLogo code line-by-line, the QL development team soon encountered a few issues that had to be addressed before moving to C#. These included the following.

Spatial input data. The files accompanying both NetLogo implementations (e.g., water.txt, settlements.txt) included impossible coordinates for a few "water points" and historical settlements. Given that this issue has a minimal impact on aggregate behaviour and the original raw data is hardly traceable, it was decided to exclude these data entries.

Scheduling and data time-series. The model scheduling was found to be shifted in respect to the palaeoenvironmental time-series data (e.g., adjustedPDSI.txt, environment.txt, water.txt), which regulate agricultural productivity in each year/location in the model. For instance, the data corresponding to the first year (800 AD) is used twice, during the `setup` and `go` procedures. The issue was solved by counting `setup` as the first year and updating the year counter at the start of time steps rather than at the end.

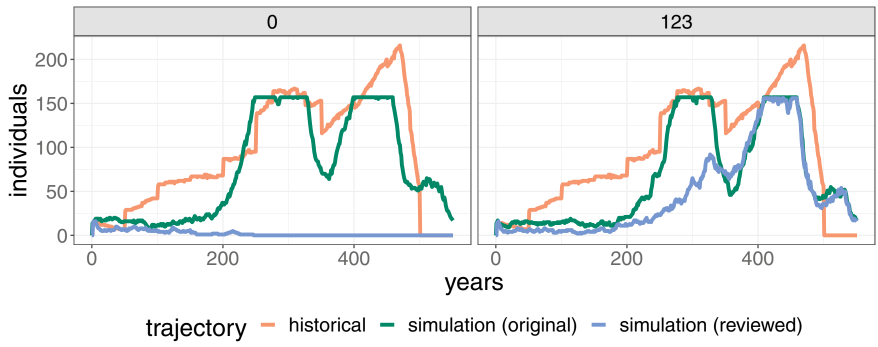

Fig. 1 Difference in trend after the revision of the Artificial Anasazi model in NetLogo. Simulations under two random seeds, 0 and 123, are given as examples

Inheritance of maize stock. In both NetLogo versions, the inheritance of maize stock, happening during household fission, was not functioning as the modellers (presumably) intended. When "fissioning", the parent household discounts a certain amount of stock, as determined by a parameter (`maize-gift-to-child`, in NetLogo library's version). However, the child household receives a different amount, completely unrelated to the parent's stock. This was corrected by stating a perfect equivalence between the amounts discounted in the parent's stock and received by the child's.

After these corrections were made, still within NetLogo, AA produced system trajectories that were already quite different from the originals (Fig. 1).

A3. Model adaptation and extension. After reviewing the code and consolidating the game concept (i.e., immersive, first-person, see Sect. 4), it became clear that the original model had to be further modified. These corrections and modifications made the simulation runs to display more path-dependent trajectories, as the success of new households was closely related to the previous success of the parent household. These are the most important changes.

Break up household population into individual members. Households are the atomic units of the AA model. These were modelled as if they were asexual organisms that are born out of a parent organism, give birth to other child organisms, and eventually die of starvation or old age. A household fitness at any given year depends on its stock of food (cultivated maize), the consumption rate per person-year, and the number of people inside. Under this design, the population of a household, e.g., five people, will appear from thin air in a given year (*a household is born*), generate new fully-populated households under certain conditions (*household fission*), and then disappear after a certain number of years (*household death*). However, this conceptualisation was considered an obstacle for designing an immersive game in first-person perspective. The solution was to expand the model by adding a "character" or "person" dimension within households. These characters are not proper agents; they are accounted in array variables inside each household agent (e.g., age = 34, 25, 7, 5, 1, indicate the ages of the five individual members in a household). Characters are the ones being born, having children, and eventually dying, while a household will only "die" if there are no characters inside. On game development, this modification was combined with a controlled random number generator to allow believable characters (with name, age, sex, lineage, etc.) to be tracked in time and space.

Convert constants and parameters. Several household parameters were re-interpreted as parametric or emergent distributions of household members variables. For instance, the consumption of maize per capita, previously applied to all households as a global parameter, became a set of parameters defining a probability distribution from which to draw values for each individual. The QL version of the model is consequently more stochastic, has fewer global parameters, and is less affected by specific parameter settings.

B. Game conceptual design

The main game concept is inspired by the NBC science-fiction television series *Quantum leap* (1989–1993). Thus, the player is an archaeologist from the future involved in an experimental technique that allows consciousness to time-travel. An accident happens and the player's consciousness travels to the past, involuntarily replacing the consciousness of a person that lived in the Ancestral Puebloan culture, formally called Anasazi, in the Long House Valley (Arizona, USA) between 800 and 1350 AD. When this happens, the course of history changes. In order to come back to the present (i.e., finish the game), the player has the task to match the games' course to the historical development (increasing a *convergence* score). This can be done by incarnating in individuals, immersing into their biographies, and influencing the behaviour of immediate peers through dialogue and social interaction. This combination of context and mechanics was considered the best solution for making the agent-level perspective compatible with immersive gameplay, given the centuries-long scale of simulations. The game flow is represented in Fig. 2.

C. Game development

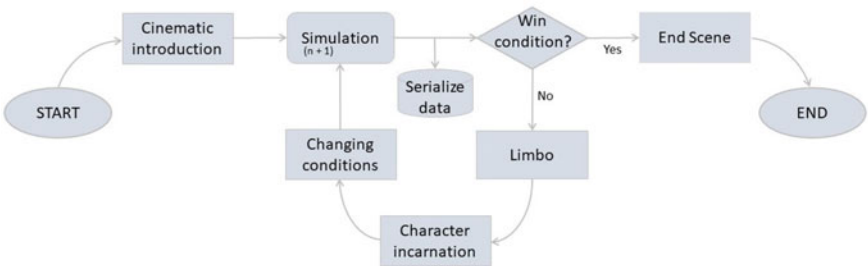

Fig. 2 *Quantum Leaper* game flow

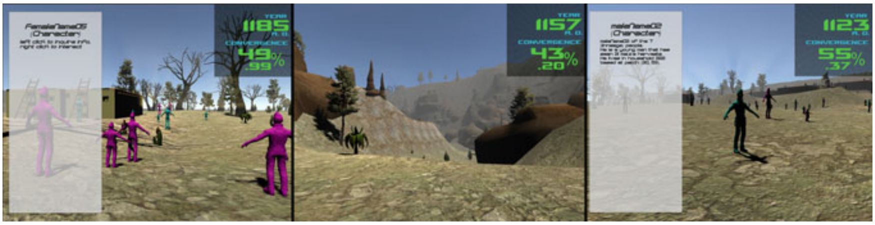

Fig. 3 Prototype in-game screenshots of the *Incarnation* scene

The Unity game engine was chosen for the implementation of the game, as it is relatively straightforward to learn progressively, allowing for fast development while containing the potential for complexity, both in terms of code and aesthetics (Fig. 3).

These were the major QL development tasks.

In-game management of simulation data. To connect simulations with gameplay effectively, one of the first tasks was to program a system to serialise and deserialise simulation data effectively. During gameplay, the system will create binary files, each containing the state of the simulation at the end of a time step (i.e. year). These files are re-written every time the simulation is run from an earlier year. Simulation data is deserialised when entering the *Incarnation* scene and used to generate or configure game objects (e.g., age affects characters' height).

Loading and decorating the 3D landscape. Because AA is placed in a real location (Longhouse Valley, USA), the development team aimed at using real-world spatial data to configure the 3D space experienced during character incarnation. However, this presented three sets of challenges: (i) finding a Digital Elevation Model (DEM) with a good-enough resolution, importing it to Unity, and making it realistic when experienced from the first-person perspective; (ii) applying terrain textures and adding the scenery (natural environment, buildings, and characters) through procedural generation; and (iii) loading and deleting terrain chunks seamlessly around the moving player, which is required given the large size of the entire valley area. After overcoming these challenges, a set of Unity-C# assets were developed and released [1].

Dialogue system. An interactive narrative system using Twine-Tracery (the grammar-expansion library Twine combined with the interactive fiction tool Tracery) was employed to mediate between player and non-player characters. The player's decisions regarding dialogue options feed information back to the simulation by modifying certain variables (e.g., convincing characters to eat less will decrease the consumption of maize of those individuals).

Artistic assets. Audiovisual elements (e.g., 3D models, textures, text, sound effects) in games are critical for player immersion. In QL, the development team used Unity's own sponsored community (Unity Asset Store), which includes several basic free assets that can be used for learning and prototyping.

User interface (UI) and game system. A minimal UI and game system were created for QL using the resources found in Unity Asset Store, including a splash and start screen, options and game start menus, a loading screen, player controllers, and a HUD (heads-up display) showing the current year and convergence percentage in the top-right corner of the screen.

QL has been developed as a side project and remains as an unfinished and unpublished prototype. This project still lacks a functional system and text base to handle dialogues, which is the primary action during gameplay and a key factor for immersion. Additionally, to reach QL's full potential, artistic assets should be curated by experts about the Ancestral Puebloans (e.g., anthropologists, archaeologists, native community representatives).

5 The Conflict Resolution: Where the Protagonist Finally Overcomes the Conflict, Learns to Accept It, or Is Ultimately Defeated by It

At the resolution point, usually the story ends. The protagonist fulfills the initial goal, does not fulfill it, or transforms it. In our case, after a close analysis of the journey, we propose the GAM Reflection Framework and invite the reader to discuss its usefulness.

How to describe in a meaningful way the integration of an ABM with a Game? Answering this question was not an easy nut to crack. As a first contribution to this answer, we propose a reflection framework. As explained by Rapoport, "[…] frameworks are neither models nor theories. Models describe how things work, whereas theories explain phenomena. Frameworks do neither; rather they help to think about phenomena, to order material, revealing patterns…" [13] (page 256). After closely examining the development of QL, especially the last sentence sounded appealing to us: as a first step in the GAM method, we think that one has to go through a structured reflection about what is being combined, how, and why. Reflection is considered the key learning activity to transform concrete experience into abstract concepts, to generalize main ideas and principles [12]. Moreover, reflection is a process that utilizes knowledge that "lies deep within (tacit knowledge)—so deep it is often taken for granted and not explicitly acknowledged, but it is the data humans use to make instinctive decisions based upon accumulated knowledge from past actions and experience" [8](page 22). As such, it seems to us of crucial importance to have useful tools that guide this process, especially in a tangled process such as using GAM designs.

The process of combining ABMs and games in a GAM design can be understood as a process of interdisciplinary research, in the sense that it involves disciplines with contrasting paradigms, forcing researchers to cross subject boundaries in order to create new knowledge, theory, and/or methods and solve a common research goal [17]. As such, the GAM Reflection Framework is an adaptation of the protocol for assessing the interdisciplinarity of models proposed by [18], which maximises the extraction of implicit knowledge and decisions. However, proposing tools seems

Table 1 The GAM reflection framework (Part 1) applied to the case of *Quantum Leaper*

PART 1 Formal reflections	
WHAT contributes to GAM	
What disciplines and knowledge bodies were involved and integrated?	
In the ABM	*Archaeology, expertise of ABM modellers*
In the Game	*Archaeology, game design, expertise of native communities (at a future point) & Expertise in the various implementation tools (e.g., Unity)*
HOW GAM is performed	
Which resources were used? Explain why these were used.	
Empirical (datasets and sources)	*Spatial data files given with the NetLogo implementations of the model; height map (or Digital Elevation Model) of the location (Longhouse Valley, Arizona, USA). Source: USGS, through terrain.party.*
Methodological (methods)	*Agent-based modelling; Game design for creating open-world 3D first-person games; General storytelling techniques (e.g., rhythm, plot devices), and visual storytelling.*
Theoretical (theories)	*Knowledge used for reviewing and extending the AA model: complex adaptative systems; human ecology and demography.*
Technical (tools)	*NetLogo (ABM preparation); Unity and C# (game development); Twine-Tracery (interactive text system); Terrain.party (obtaining terrain heightmap); GIMP (image editing); Audacity (audio editing); Free Music Archive, SoundCloud, Freesound (obtaining sound effects and music).*
WHY GAM is used	
What new knowledge is produced by the GAM design? What problem it aims to solve?	
Epistemological (to produce new understanding and knowledge)	*Experience a multiagent system from a first-person perspective; to enable new insights about the model and the dynamics of the systems it aims to represent.*
Instrumental (to solve a problem or a societal challenge)	*Bridge the gap between the formal, unintuitive definition of complex socio-ecological phenomena found in ABMs and the more general understanding of how society relates to environment, particularly but not only by non-modellers.*

easier than applying them. Thus, in order to give a taste of its applicability and encourage its use, we provide a demonstration on the QL case, which, out of space consideration, is included directly in the framework (Tables 1 and 2).

The core assumptions of the GAM Reflection Framework are: (1) that the analysed application includes an ABM (pre-existing or developed from scratch); (2) that the analysed application includes a Game, with all the necessary elements of a game (e.g., mechanics, dynamics, aesthetics); (3) that both the ABM and the Game co-

Table 2 The GAM reflection framework (Part 2) applied to the case of *Quantum Leaper*

PART 2 General reflections	
Team (organisation, communication etc.)	*QL was developed by a two-person team working mostly side-by-side on different tasks. It was noticeable that the team lacked some key skills, particularly those of a trained artist and writer. Most work was done in Unity and, at the time (2017), sharing Unity projects in an orderly way was more challenging than today. Unity now offers a built-in cloud service with version control, through which collaborators can work on the same project.*
Game engines or platforms (pros and cons, challenges etc.)	*Unity is surely one of the most comprehensive and accessible game engines available at present. The QL prototype was developed relatively fast thanks to this and given the vast online community of users sharing Unity assets, including C# code snippets. However, it is a tool in constant change and improvement, making learning new features a never-ending necessity. Engaging with some kind of formal learning (e.g. MOOCs) recommendable to make the most of it.*
Transparency and rigour (measures taken etc.)	*The team kept an ongoing design document were notes about advancements and new ideas were stored and shared. The code base of the ABM and game system has been constantly tested, refactored and annotated, aiming at making it reproducible and readable for a wider public. Screen video recordings were made after different milestones in development and shared on YouTube.*
Stakeholders (interaction etc.)	*(Pending until after the game is published)*
Outputs/outcomes (what was produced, how it was received etc.)	*(Pending until after the game is published)*

exists and are integrated in one single application; thus, they run simultaneously; (4) that the GAM design has a research purpose.

The GAM Reflection Framework is divided in two parts: reflections structured around the interdisciplinarity of the endeavour (Part 1 Formal reflections; Table 1) and reflections structured around the general process of building the agent-based game (Part 2 General reflections; Table 2). While reflection are usually undertaken at the end of a task or activity, we encourage the possible users to use this framework before, during, and/or after the GAM design process is finished. We base this recommendation on findings from research on learning, which explain that in order to make reflection useful for development of cognitive levels and not only of the affective levels, reflection should be implemented in a well-structured, intentional manner with purposeful fidelity throughout the course of activities [5].

We envisage four types of users of the GAM Reflection Framework: GAM practitioners, coordinators of research that includes GAM designs, ABM modellers, and game designers. GAM practitioners can use the framework to increase the value of learning from their own practices, in addition to increasing the rigour and transparency of these practices. Using the framework can also help these users to express clearly the interdisciplinary characteristics of their agent-based game. Coordinators of research that includes GAM designs can use the tool to plan the research tasks, while ABM modellers and game designers can use it as guidance to structure the collaborative work in interdisciplinary teams that use these designs or to assess whether such work is something that they want to add to their portfolio.

6 Conclusion

Building on experience with interdisciplinary research, on insights from using reflection as a learning tool, and the description of the steps taken to transform the NetLogo ABM "Artificial Anasazi" into a Unity-based immersive first-person video game, *Quantum Leaper*, this paper attempts to "discipline", or bring some methodological organisation, in the field of combining ABM and Games. As such, this study provides a framework for reflections during the process of combining these two. We aim at contributing to the discussion and consolidation of methodological principles that are generally applicable to research using GAM, the GAM Reflection Framework. We present a brief demonstration of this framework by examining the *Quantum Leaper* video game. This framework is intended as a tool that can be combined with other approaches and frameworks, contributing to the GAM field development. The framework is a potentially learning-rich tool for GAM practitioners, coordinators of GAM designs-based research, ABM modellers, and game designers alike.

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Appendix A: Selected Literature

From: Szczepanska et al., 2022a

Table A1. List of items that met the inclusion criteria and were included in the content analysis of this study (T = research design type).

#	T	Reference
1	1	Abrami, G., & Schlueter, M. (2009). Building an agent-based model for exploring how informal rules impact the functioning of newly established water user associations in central Asia. *Conference Proceedings - 6th Conference of the European Social Simulation Association (SSC2009)*.
2	5	Adamatti, D. F., Sichman, J. S., Bommel, P., Ducrot, R., Rabak, C., & Camargo, M. E. S. A. (2005). JogoMan: A prototype using multi-agent-based simulation and role-playing games in water management. *Joint Conderence on MultiAgent Modelling for Environmental Management* (CABM-HEMA-SMAGET), 1–18. For further details and a discussion on the GMABS methodology (Games and Multi-Agent-Based Simulation) see: Adamatti, D. F., et al. (2009). An analysis of the insertion of virtual players in GMABS methodology using the Vip-JogoMan prototype. *Journal of Artificial Societies and Social Simulation,* 12(3) 7. https://www.jasss.org/12/3/7.html
3	3	Anand, N., Meijer, D., van Duin, J. H. R., Tavasszy, L., & Meijer, S. (2016). Validation of an agent based model using a participatory simulation gaming approach: The case of city logistics. *Transportation Research Part C: Emerging Technologies*, *71*, 489–499. https://doi.org/10.1016/j.trc.2016.08.002
4	6	Anderson, B., Coulter, S., Orlowsky, R., Ruzich, B., Smedley, R., Purvis, M., Learmonth, G. P., & Gerling, G. J. (2017). Designing user experiences for policymakers in serious games in the domain of global food security. *Systems and Information Engineering Design Symposium*, 89–94. https://doi.org/10.1109/SIEDS.2017.7937759
5	3	Barreteau, O., Bousquet, F., & Attonaty, J. M. (2001). Role-playing games for opening the black box of multi-agent systems: Method and lessons of its application to Senegal River Valley irrigated systems. *Journal of Artificial Societies and Social Simulation*, *4*(2). https://ideas.repec.org/a/jas/jasssj/2000-18-1.html

6	6	Becu, N., Amalric, M., Anselme, B., Beck, E., Bertin, X., Delay, E., … Rousseaux, F. (2017). Participatory simulation to foster social learning on coastal flooding prevention. *Environmental Modelling and Software*, *98*, 1–11. https://doi.org/10.1016/j.envsoft.2017.09.003
7	3	Belem, M., Bazile, D., & Coulibaly, H. (2018). Simulating the impacts of climate variability and change on crop varietal diversity in Mali (West-Africa) using agent-based modeling approach. *Journal of Artificial Societies and Social Simulation*, *21*(2). https://doi.org/10.18564/jasss.3690
8	8	Bhattacharya, K., Takko, T., Monsivais, D., & Kaski, K. (2019). Group formation on a small-world: Experiment and modelling. *Journal of The Royal Society Interface*, *16*(156), 20180814. https://doi.org/10.1098/rsif.2018.0814
9	6	Briot, J. P., de Azevedo Irving, M., Filho, J. E. V., de Melo, G. M., Alvarez, I., Sordoni, A., & de Lucena, C. J. P. (2016). Participatory management of protected areas for biodiversity conservation and social inclusion: Experience of the SimParc multi-agent-based serious game. In *Multi-Agent-Based Simulations Applied to Biological and Environmental Systems*, 295–332). https://doi.org/10.4018/978-1-5225-1756-6.ch013
10	3	Castella, J. C., & Verburg, P. H. (2007). Combination of process-oriented and pattern-oriented models of land-use change in a mountain area of Vietnam. *Ecological Modelling*, *202*(3–4), 410–420. https://doi.org/10.1016/j.ecolmodel.2006.11.011 For a more detailed description of methodological details, see Castella, J. C., et al. (2005). Participatory simulation of land-use changes in the Northern Mountains of Vietnam: the combined use of an agent-based model, a role-playing game, and a geographic information system. *Ecology and Society,* 10(1): 27.
11	4	Cedeno-Mieles, V., Hu, Z., Ren, Y., Deng, X., Adiga, A., Barrett, C., … Self, N. (2020). Networked experiments and modeling for producing collective identity in a group of human subjects using an iterative abduction framework. *Social Network Analysis and Mining*, *10*(1), 11. https://doi.org/10.1007/s13278-019-0620-8
12	1	D'Aquino, P., & Bah, A. (2014). Multi-level participatory design of land use policies in African drylands: A method to embed adaptability skills of drylands societies in a policy framework. *Journal of Environmental Management*, *132*, 207–219. https://doi.org/10.1016/j.jenvman.2013.11.011

13	5	Daré, W., Venot, J. P., Page, C. L., & Aduna, A. (2018). Problemshed or watershed? Participatory modeling towards IWRM in North Ghana. *Water (Switzerland)*, *10*(6), 721. https://doi.org/10.3390/w10060721
14	6	Delaney, L., Kleczkowski, A., Maharaj, S., Rasmussen, S., & Williams, L. (2013). Reflections on a virtual experiment addressing human behavior during epidemics. *Simulation Series*, *45*(11), 131–138.
15	2	Dubois, E., Barreteau, O., & Souchère, V. (2013). An agent-based model to explore game setting effects on attitude change during a role playing game session. *Journal of Artificial Societies and Social Simulation*, *16*(1), 1–14. https://doi.org/10.18564/jasss.2065
16	5	Dumrongrojwatthana, P., Le Page, C., Gajaseni, N., & Trébuil, G. (2011). Co-constructing an agent-based model to mediate land use conflict between herders and foresters in northern Thailand. *Journal of Land Use Science*, *6*(2–3), 101–120. https://doi.org/10.1080/1747423X.2011.558596
17	1	Dupont, H., Gourmelon, F., Rouan, M., Le Viol, I., & Kerbiriou, C. (2016). The contribution of agent-based simulations to conservation management on a Natura 2000 site. *Journal of Environmental Management*, *168*, 27–35. https://doi.org/10.1016/j.jenvman.2015.11.056
18	2	Gomes, S., Dias, J., & Martinho, C. (2019). GIMME: Group interactions manager for multiplayer serious games. *2019 IEEE Conference on Games (CoG)*, *2019*, 1–8. https://doi.org/10.1109/CIG.2019.8847962
19	4	Gu, J., Huang, J.-P., & Chen, Y. (2018). A preliminary study of human decision-making, risk attitude, and social preference on knowledge management. In *Developmental Cognitive Neuroscience*, *591*, 297–311. https://doi.org/10.1007/978-3-319-60591-3_27
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21	6	Guyot, P., & Honiden, S. (2006). Agent-based participatory simulations: Merging multi-agent systems and role-playing games. *Journal of Artificial Societies and Social Simulation*, *9*(4). https://www.jasss.org/9/4/8.html
22	3	Joffre, O. M., Bosma, R. H., Ligtenberg, A., Tri, V. P. D., Ha, T. T. P., & Bregt, A. K. (2015). Combining participatory approaches and an agent-based model for better planning shrimp aquaculture. *Agricultural Systems*, *141*, 149–159. https://doi.org/10.1016/j.agsy.2015.10.006

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27	3	Le Pira, M., Marcucci, E., & Gatta, V. (2017). Role-playing games as a mean to validate agent-based models: An application to stakeholder-driven urban freight transport policy-making. *Transportation Research Procedia*, *27*, 404–411. https://doi.org/10.1016/j.trpro.2017.12.060
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47	4	Verwaart, T., Dijkxhoorn, Y., Plaisier, C., & van Wagenberg, C. (2019). Agent-Based Simulation of Local Soy Value Chains in Ghana. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics): Vol. 11805 LNAI*, 654–666). https://doi.org/10.1007/978-3-030-30244-3_54
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49	4	Villamor, G. B., & van Noordwijk, M. (2016). Gender specific land-use decisions and implications for ecosystem services in semi-matrilineal Sumatra. *Global Environmental Change*, *39*, 69–80. https://doi.org/10.1016/j.gloenvcha.2016.04.007
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51	5	Yang, L., Zhang, L., Philippopoulos-Mihalopoulos, A., Chappin, E. J. L., & van Dam, K. H. (2020). Integrating agent-based modeling, serious gaming, and co-design for planning transport infrastructure and public spaces. *URBAN DESIGN International*. https://doi.org/10.1057/s41289-020-00117-7
52	6	Zhang, J., Issa, R. A. R., & Liu, R. (2016). Development of an Immersive game for Human Behavior data Collection. *Construction Research Congress*, 2332–2339.

Appendix B: In-depth Description of Six Research Design Types

From: Szczepanska et al., 2022a

Research design type 1 (Game ⇒ ABM) is characterised by a sequence that moves from the game to the ABM. The game leads the process, although the sequence may be repeated over multiple iterations to include multiple data sources, and is used as a facilitation tool to collect, discuss, and integrate stakeholder knowledge into an overarching model concept. The ABM is constructed after the game and reflects the components, scheduling processes, and flow of the game. Subsequently, both the components represent the same target system. Type-1 research designs are most commonly found in research projects with stakeholder involvement at their core. The game is then used as a vehicle to develop a concept model in a participatory fashion. We found nine publications in which this research design was used, wherein RPGs were applied as a participatory approach, in the field of natural resource management. Six of these articles labelled their approach as companion modelling (A1#17 (Table A1, row #17), A1#25, A1#33, A1#39, A1#40, and A1#50), and three refrained from self-description (A1#1, A1#12, A1#48).

The sequence of **research design type 2 (Game ⇏ ABM)** begins with either creating a game or using an existing game. As in type 1 (Game ⇒ ABM), the ABM is developed or employed after the game. However, in the type-2 research design, the ABM depicts a different target system (section 2.2.). The ABM is constructed with the goal of improving the game's performance or simulating the game itself. It is a relatively rare occurrence in our dataset (three articles) and is applied to explore player decision-making (A1#45), the effects of the game settings on player attitude changes (A1#15), or introducing group management with the purpose of enhancing the performance of a serious game in achieving learning goals (A1#18). In all these studies, the system simulated in ABM is either a part of the system defined for the game or a different target system.

In **research design type 3 (ABM ⇒ Game)**, the sequence transitions from the ABM to the game. A research project initiates with an (simple) ABM of the investigated phenomenon. The game is constructed either to mirror the ABM or highlight its specific aspects. Both the ABM and game explore the same target system and employ identical or vastly similar mechanics. Type 3 research designs are found in community-based approaches aimed at engaging stakeholders and improving communication among different interest groups. Five of eight papers comprising the type-3 research design explore natural resource management using analogue RPGs to engage stakeholders in validating (A1#5, A1#7, A1#10, and A1#42) or calibrating (A1#22) the ABM. Two additional articles are related to urban logistics and employ RPGs to validate and improve model ontology and dynamics (A1#3) or to test the predictive ability of the ABM (A1#27). The last publication of type 3 refers to ethics and trust and exercises the game for ABM verification and validation purposes (A1#28).

Research design type 4 (ABM ⇏ Game) starts with the creation of an ABM and the subsequent game is aimed at collecting additional knowledge to feed back into the ABM. Although observations from the gaming session are applied to enhance the initial ABM, the game itself is a stand-alone product representing a distinct target system. Type-4 designs are mainly employed in studies investigating human interactions in social or sociotechnical systems. While the purpose of the game can be similar to the one in type-3 designs (i.e., validating an ABM), the approach here offers opportunities to extend prevailing models with new dynamics or perform triangulation by linking results. The type-4 approach employs games in experimental settings with the goal of extending or tuning existing ABMs. Four of the nine type-4 publications were focused on natural resource management and used digital RPGs to collect data regarding player behaviours (A1#36, A1#41, and A1#49). In all these studies, the subjects interacted directly with a computer via a user interface in an experimental setting. The digital RPGs were used in a similar fashion to that in the analogue games described in type 3. They are used as a data collection set-up to test different intervention scenarios with the players in an experimental setup (A1#19) to evaluate and calibrate ABMs through controlled laboratory experiments with an online game platform (A1#30, A1#37) and anagram games (A1#11), and to extend the capacities of agents to make them more "human-like" (A1#8). One example (A1#47) comprises the use of behavioural economics games with a mix of methods, e.g., desk research and interviews, to calibrate simulations.

Research design type 5 (Game + ABM) showcases studies wherein the ABM is an inherent element of the game and is therefore created as a part of the game development. During a gaming session, the ABM simulates complex mechanics (e.g., dynamic effects on an environment resulting from player interactions). Depending on what simulated effects are required to support the gameplay, the target systems may be equivalent or different. As in the cases of types 1 and 3, type-5 research designs in our sample study comprise the use of community-based approaches. Five of the six studies were on the natural resource management domain and combined an ABM with an RPG. In these studies, the ABM is used to calculate and represent the impacts of player actions on an ecological system (water management (A1#2, A1#13, and A1#43); biodiversity (A1#38); or land management (A1#16)). In one study, the ABM is used to supplement a city logistics game by visualising an additional layer of information (A1#51).

Research design type 6 (ABM = Game) describes projects in which an ABM is built as a game either by creating a brand-new application or transforming an existing ABM into a game. As the ABM and game have one application, they represent one target system. Their components are intertwined and comprise the application's mechanics, rules, and user interface(s). The type-6 research design is becoming increasingly popular (17 examples in this review: between 2017 and 2018, type 6 represented more than 50% of the analysed publications) and relatively diverse. It is used in community-based approaches and studies that research human behaviour, explore socio-technological systems, or experiment with business games. More recently, ABM=games (or agent-based simulation games) have been the most common research design to support policy development. The first type-6 study (in our sample study) was focused on describing emissions trading (A1#32). Subsequently, it was applied in a variety of fields, e.g., public health (A1#14, A1#24, and A1#31), construction management (A1#52), security (A1#44), group dynamics (A1#29), and businesses games (A1#23 and A1#46). Moreover, the type-6 research design has been used in studies engaging stakeholders, e.g., in natural resource and risks management (A1#4, A1#6, A1#9, A1#20, A1#21, and A1#26), air-traffic management (A1#34), and humanitarian logistics (A1#35)

In addition, there are a few research setups that include multiple design types in one study. For example, a study initially designed using the types 1 or 3 research design sequence can transition to a type 5 at a later stage if additional resources are available (e.g., A1#13).

Appendix C: GAM Documentation Scheme

From: Szczepanska et al., 2022a

Table C1 Games and Agent-based Models (GAM) Documentation Scheme. Answer options are provided in square parentheses.

A) General aspects	6. Purpose of the study. [open ended] 7. Research questions of the study. [open ended] 8. Application field. [open ended] 9. Type of GAM. [1. Game --> ABM, 2. Game -/-> ABM, 3. ABM --> Game, 4. ABM -/-> Game, 5. Game + ABM, 6.ABM = Game] 10. Additional comments. [open ended]
B) GAM	8. Purpose of using the GAM methodology. [open ended] 9. GAM design (e.g., sequences, phases, procedures, iterations, and information flow). [open ended] 10. How the game and ABM are linked (e.g., specifically, which information from gameplay was used to validate the ABM, how was the gameplay data used to inform ABM rules, and how ABM simulations are used in the game. [open ended] 11. Limitations of the specific GAM implementation. [open ended] 12. How the use of GAM contributed to answering the research questions of the study. [open ended] 13. Advice for others. [open ended] 14. Additional comments. [open ended]
C) Game	1. Target system. [open ended] 2. Kind of game. [commercial off-the-; built for purpose, but not for this study; built for purpose, for this study]. 3. Game type. [analogue; computer-based; mixed] 4. Game category: a. Dice and luck: dice games, start-goal-games, search and catch games b. Layout games: letter layout games, lottery games, figure layout games, picture layout games c. Thinking games: strategic games, tactical games, combination games, memory games, solitary games d. Quiz/Communication games: question-and-answer games, quiz games, fortune-telling games, creativity games e. RPGs and simulations: economy games, criminal games, adventure games, conflict games f. Dexterity games: dexterity games, action games, reaction games, sport games g. Other: _______________. 5. Who the players are (e.g., stakeholders, students, fellow researchers, and general public). [open ended] 6. How the players were selected. [open ended] 7. Game objective. [open ended] 8. Core game mechanics. [open ended] 9. Data collected from gameplay. [open ended] 10. How is the data collected from gameplay (e.g., observation and tracking). [open ended] 11. If debriefing was performed and how this was done (If debriefing was not performed, provide a reason for that decision). [open ended]] 12. Data collected after the gameplay. [open ended] 13. How is the data collected after the gameplay (e.g., questionnaire, interview, or focus group). [open ended]. 14. What the ABM adds that would not be known otherwise. [open ended] 15. Additional comments. [open ended]

D) ABM

1. Target system. [open ended]
2. Link to fill in documentation/reporting protocol/scheme: ______________
3. What the ABM adds that would not be known otherwise. [open ended]
4. Additional comments. [open ended]

Appendix D: Figures

From: Szczepanska et al., 2022a

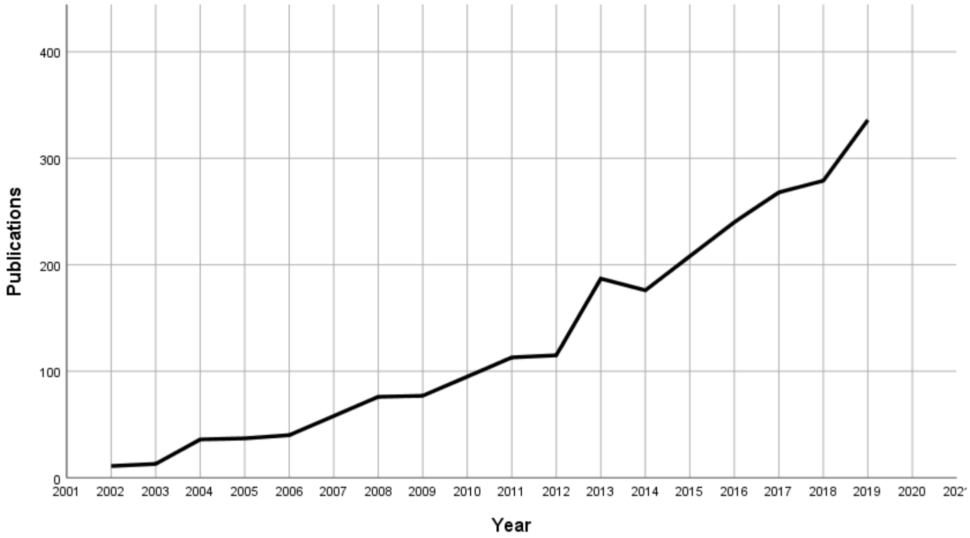

Figure D1 Results obtained on searching for the keyword "agent-based model" on ScienceDirect (23.03.2021) filtered by "Year" and "Subject areas" (environmental, agricultural, and biological sciences).

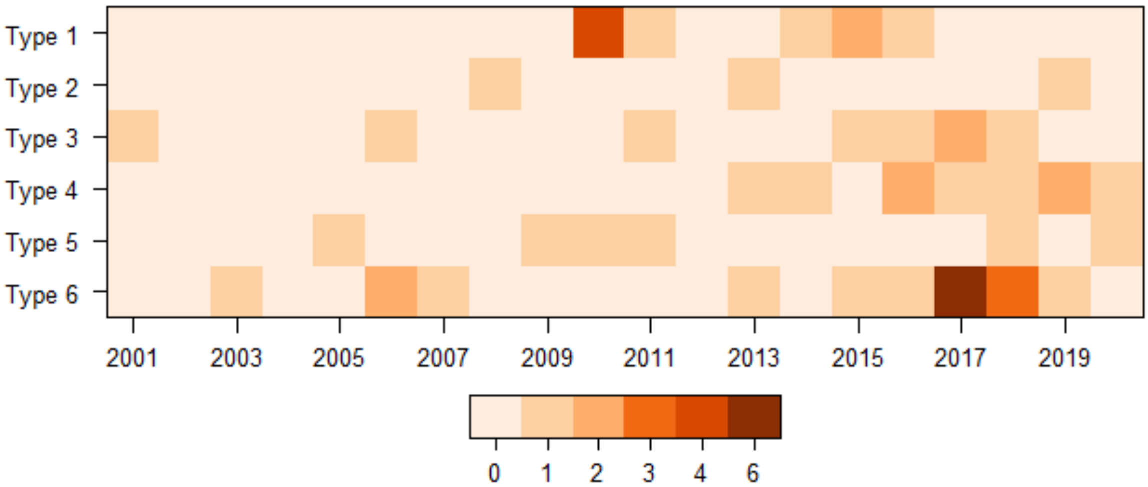

Figure D2 Publications per year per research design type.

	Type 1	*Type 2*	*Type 3*	*Type 4*	*Type 5*	*Type 6*
Natural Resource Management	9		5	4	5	4
Group Dynamics		2		3		2
Public Health						3
City Logistics			2		1	
Attitude-Behaviour Relation		1		1		
Natural Risk Management						2
Methodology, ABM Validation			1			
Air Traffic Management						1
Business Management						1
Construction Management						1
Organizational Management				1		
Emission Trading						1
Humanitarian Logistics						1
Security						1
	9	**3**	**8**	**9**	**6**	**17**

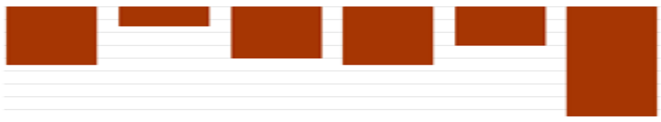

Figure D3 Number of publications per research design type

Appendix E: Prisma Diagram Game and ABM SLR (2021-2023)

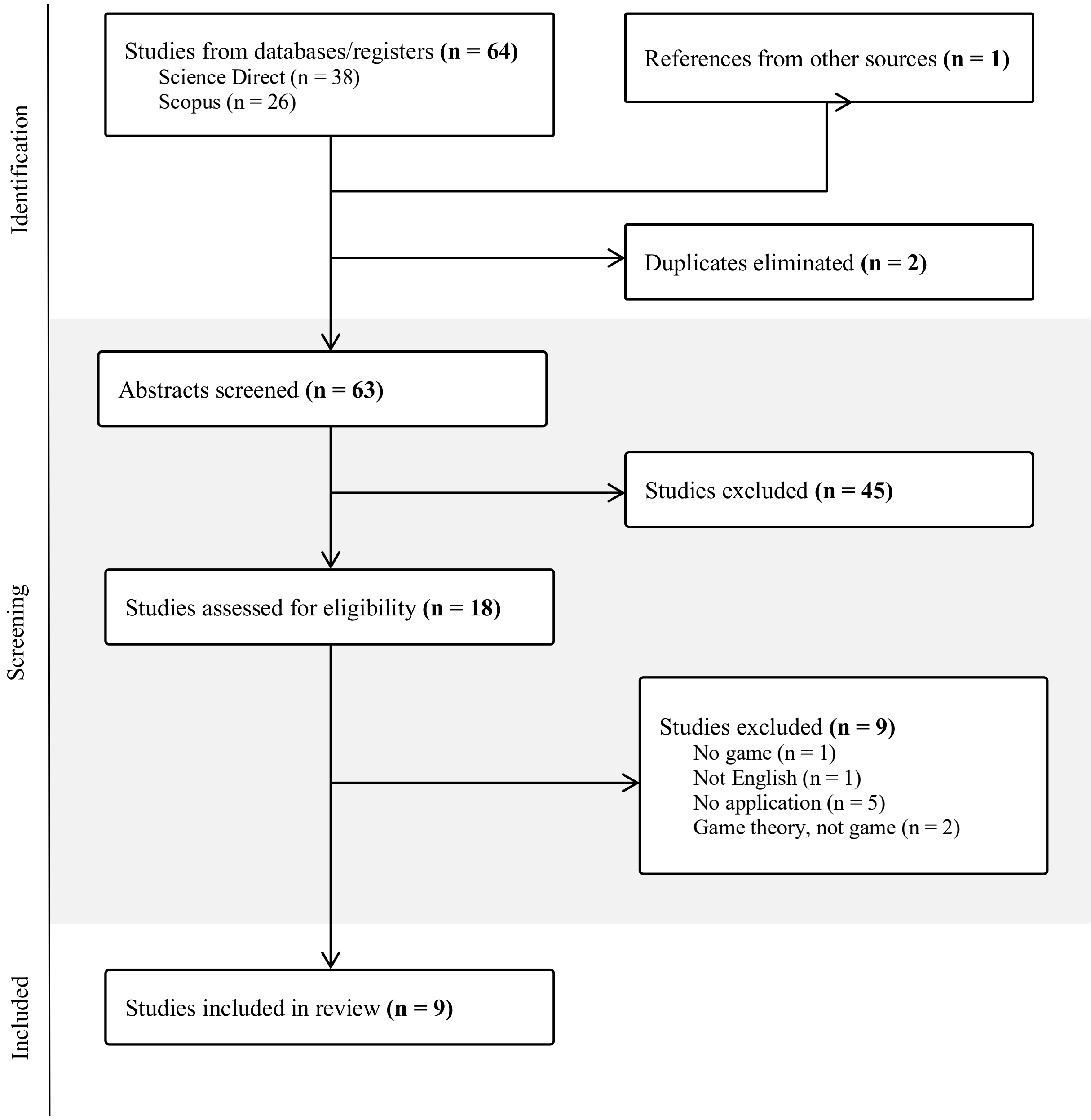

Figure E1 Flow of Information Through the Different Phases of the SLR. Search date: 14.07.2023