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**Communicating Agent-Based Models to Stakeholders: A
Semi-Automated Framework and Case Study in Forest-based SES**

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Introduction

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Communication of simulation models to stakeholders remains a fundamental and persistent concern with agent-based models [Grimm 2005], especially in settings where modeling is part of a negotiation process such as companion modelling [Barreteau 2003]. While ABMs are increasingly used to capture the complexity of real-world systems, their value often remains inaccessible to the people who are meant to use or benefit from them. Although participatory approaches such as co-design, visualization tools, and structured documentation have enabled stakeholder involvement, the technical nature of ABM logic, rules, and outputs still often renders them opaque. This complexity contributes to their perception as “black boxes” [Bommel 2011, Taghikhah 2022] – systems that are characterized and evaluated primarily through observable inputs and outputs, while their internal mechanisms remain opaque or inaccessible. In this sense, models are understood primarily by their developers and not always accessible to the broader decision-making processes they are intended to support.

This communication gap persists even as agent-based modeling matures as a methodology. Although documentation protocols, structured diagrams, and participatory modeling techniques have made models more transparent during development, the post-development phase – when simulation outputs are available for interpretation, reflection, and application – remains poorly supported. At this stage, stakeholders could engage most meaningfully with the model to validate its assumptions, explore policy scenarios, and inform decisions. Yet this potential is rarely realized, due in large part to the absence of effective **tools to bridge the cognitive and technical divide between modelers and stakeholders**. In practice, these efforts are also limited by resource constraints, as research budgets and timelines often do not account for the time- and cost-intensive process of communicating and restituting model outcomes.

Addressing this gap requires more than better documentation or clearer visualizations; it calls for the development of tools explicitly designed to translate complex model behavior into forms that are accessible, interpretable, and meaningful to those outside the modeling team. Without such tools, the **post-development use of ABMs** remains largely confined to academic publications, reports, or static

presentations. This limits opportunities for model reuse, scenario exploration, and co-interpretation of simulation results. In participatory modeling contexts, it also weakens the legitimacy of the model and reduces stakeholder trust, ultimately undermining the potential of ABMs to support inclusive, evidence-informed decision-making.

This challenge is particularly pronounced in the study of social–ecological systems (SES) – dynamic systems in which human and environmental components interact in complex, adaptive, and often unpredictable ways. Modeling SES is especially demanding because of the heterogeneity of actors, the presence of feedback loops, and the need to balance multiple, often competing objectives. These conditions also make validation processes inherently fuzzy, as no single criterion can fully capture the accuracy or legitimacy of a model across different perspectives. Agent-based models are well-suited to represent these dynamics, as they can simulate the behavior of individual agents (e.g., humans, institutions, ecosystems) and reveal how system-level patterns emerge from localized interactions. At the same time, the multiplicity and importance of socio-economic and biophysical factors require modelers to make selective decisions about what is represented. Without effective tools for communication, both this asserted selection and the very features that make ABMs powerful for SES research – rich detail, dynamic complexity, and emergent behavior – can reinforce their “black box” perception.

The LUNTIAN case study illustrates these challenges in practice. Focusing on industrial tree plantations in the Philippines, LUNTIAN provides a concrete setting in which to test both the difficulties and possibilities of bridging ABM communication gaps. By examining social–ecological interactions in this system, the case study demonstrates how simulation models can be made more relevant and interpretable for diverse stakeholders. Importantly, the utility of ABMs in SES contexts depends not only on technical sophistication but also on accessibility: forest managers, community leaders, policymakers, and researchers must be able to understand and reflect on what the model reveals about the system they inhabit, what is missing in the model, and what is not compliant with the actors’ perceptions of the model. If insights remain locked in code or comprehensible only to specialists, their practical value diminishes. Conversely, when stakeholders can see, question, and learn from model behavior, ABMs become powerful tools for shared understanding, collaborative planning, and adaptive governance.

1.1 Contributions

This dissertation addresses the urgent yet underexplored question: *How can agent-based models be more effectively communicated to stakeholders during and after development?* It argues that the success of ABMs in applied settings hinges not merely on their design and results, but on their accessibility – on whether they can be understood, trusted, and re-used by those they aim to serve. Unlike more traditional modeling approaches that often rely on aggregated equations or system-level

dynamics, ABMs generate outcomes through the interactions of numerous heterogeneous agents, governed by detailed rules and assumptions. This richness and bottom-up structure make them especially powerful for studying complex systems, but also more vulnerable to being perceived as “black boxes.” The opacity of agent-level rules and emergent behaviors can induce greater mistrust among stakeholders, reinforcing the need for effective communication. To address this challenge, this work emphasizes post-development communication and proposes both conceptual insights and practical tools

The first contribution is a systematic scoping review of 65 academic publications, which categorizes communication tools and participation forms in ABM projects. This review surfaces three major gaps in current practice: (1) communication is predominantly focused during development, with limited post-development support; (2) emergent behaviors – central to the explanatory power of ABMs – are rarely conveyed effectively; and (3) few studies systematically evaluate whether their communication methods improve stakeholder understanding. These findings call for novel approaches that not only bridge technical and non-technical audiences, but also do so systematically and transparently.

While structural descriptions of models (e.g., UML diagrams, ODD protocols, or code documentation) are useful for conveying design intent, they often fail to capture the dynamic behavior of agent-based models as they unfold over time. For stakeholders, what matters is less the abstract representation of entities and rules, and more the observable consequences of interactions within the simulation. Logs generated during execution provide a direct record of these dynamics: they trace how agents act, interact, and collectively produce emergent outcomes. By focusing on simulation traces rather than static structures, communication shifts from explaining what the model is to showing what the model does. This perspective emphasizes process and outcome over technical specification, aligning communication more closely with the questions and concerns of decision-makers, practitioners, and communities.

To address this challenge, the second contribution is the development of **ABM-VISTA (Agent-Based Model – Visualization & Interpretation of Simulation Traces for Accessibility)**, a semi-automated framework that transforms raw simulation logs into interpretable visualizations and natural language narratives. Drawing from process mining and large language models, ABM-VISTA constructs graphical and textual representations of model behavior, allowing stakeholders to trace how decisions unfold and to comprehend system-wide outcomes without parsing code or statistical graphs. In doing so, it reframes model communication not as an ancillary activity, but as a fundamental design consideration. By using large language models (LLMs) to interpret simulation logs, the approach reframes communication as an integral part of model design. Instead of treating communication as a post-hoc add-on – limited to documentation or static presentations – it embeds interpretability within the modeling pipeline itself, making model behavior accessible to both developers and stakeholders.

The third contribution is the design and implementation of **LUNTIAN**, an

agent-based model simulating the governance dynamics of an experimental industrial tree plantation in the Philippines. Developed in close collaboration with local actors, LUNTIAN incorporates social agents (e.g., laborers, investors, university managers) and biophysical agents (e.g., trees, plots) interacting under varying regulatory and behavioral scenarios. It provides a concrete context for demonstrating the application and utility of ABM-VISTA.

Finally, the utility of ABM-VISTA is demonstrated through a case study involving LUNTIAN ABM. Applying ABM-VISTA to this context, the study illustrates how automated narrative generation and process mapping can facilitate meaningful post-development communication, helping stakeholders better understand model structure, internal dynamics, and possible emergent outcomes. Evaluations – including preliminary usability testing and comparative assessments – show that ABM-VISTA improves model transparency and contributes to better stakeholder comprehension.

1.2 Manuscript Organization

This manuscript is organized into six chapters. **Chapter 1** provides a general overview and outlines the manuscript’s objectives. **Chapter 2** presents a scoping review of the literature on ABM communication strategies, analyzing 65 articles to identify dominant tools, forms of participation, and gaps in practice. The content of this chapter is based on an article published in the *Journal of Artificial Societies and Social Simulation* [Arnejo 2025a]. **Chapter 3** introduces the ABM-VISTA framework, detailing its components and demonstrating its application to a benchmark model. This chapter builds on a paper published in the proceedings of the 26th International Workshop on Multi-Agent-Based Simulation (MABS 2025) [Arnejo 2026]. **Chapter 4** describes the LUNTIAN agent-based model, developed to simulate forest-based resource governance in the Philippines, including model design and scenario-based exploration. It draws on two papers published in the journal *Forests* [Arnejo 2023, Arnejo 2025b]. **Chapter 5** applies ABM-VISTA to LUNTIAN, demonstrating its utility in supporting post-development communication and enhancing stakeholder comprehension, supported by qualitative evaluation. Finally, **Chapter 6** concludes the manuscript by summarizing the main contributions, reflecting on limitations, and identifying future research directions for advancing stakeholder communication in agent-based modeling. Additional supporting material is provided in the Appendices, including coding schemes (**Appendix A**), and model references (**Appendices B–F**). Several parts of this work were also presented at international conferences, including GAMA Days 2021, the 11th International Congress on Environmental Modelling & Software (iEMSs 2022), and GAMA Days 2024, which provided valuable feedback for refining the methodology and communication framework. Together, these chapters present a cohesive methodology for improving the accessibility and interpretability of ABMs, towards better application of complex models in sustainable systems management.

Communicating Agent-Based Models to Stakeholders: A Scoping Review

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Building on the general concerns around the communication of Agent-Based Models introduced in Chapter 1, this chapter narrows the focus by presenting a systematic scoping review of 65 peer-reviewed studies. The review aims to map how ABMs have been communicated to stakeholders, to identify persistent gaps, and to highlight opportunities for more effective engagement. This chapter also serves as a foundation for the methodological framework developed in Chapter 3. Parts of this analysis were published in the *Journal of Artificial Societies and Social Simulation* [Arnejo 2025a].

2.1 Introduction

Agent-based models (ABMs) have attracted attention across the social sciences and ecology for studying complex adaptive systems. Over recent decades, they have also been applied to social–ecological systems, where accurately representing agents and their interactions requires incorporating local stakeholder knowledge. As simulation models increasingly engage stakeholders directly or indirectly, effective communication becomes critical to project success [Waldherr 2013, Haveman 2015, Rumeser 2016]. For ABMs in particular, stakeholder comprehension often governs perceived utility and adoption, with trust and confidence playing an outsized role [Lee 2015]. Here, “communicate” was used to mean conveying an ABM’s design, structure, functioning, and outputs to stakeholders in order to improve understanding, foster engagement, and enable application. In this framing, communication is investigated less in terms of its political or normative value, as in Arnstein’s conception of communication as a condition of power [Arnstein 1969], and more in terms of its quality and efficiency: the degree to which it minimizes ambiguity, ensures accurate transmission, and aligns interpretation between modelers and stakeholders. Clarifying the role stakeholders occupy in a given project – whether as forces represented in the simulation, as agents encoded in it, as co-designers in model building, or as users in negotiation and decision processes where the model serves as a boundary object – allows communication methods and evaluation criteria to be aligned accordingly.

While opacity is a general modeling risk, it is heightened in ABMs by micro-level heterogeneity and interaction rules that do not scale proportionally to macro outcomes and by emergent macro-patterns with nonlinear sensitivities [Bonabeau 2002], as well as by code-centric implementations distributed across multiple modules – for example, Repast Symphony, an open-source ABM toolkit whose architecture is “based on central principles important to agent-based modeling” and explicitly calls for a “strict separation between models, data storage, and visualization” [Rep 2024]. Taken together, these features can leave non-modelers perceiving ABMs as “black boxes” even when formal documentation exists [Bommel 2011, Taghikhah 2022]. Such opacity has contributed to reluctance among prospective users to trust or adopt the approach [Grimm 2012, Sun 2016, Cartwright 2016,

Tehrani 2020], and efforts to standardize ABM reporting have faced persistent difficulties despite recent progress [Collins 2015, Daly 2022]. Clearly, more standardized communication is essential to enable non-specialists and practitioners to understand and trust ABMs, thereby supporting broader adoption and application [Polhill 2008].

Another challenge lies in promoting the reuse of developed models to improve research efficiency [Polhill 2009, Müller 2014]. In this context, technical users – modelers and developers who will run, inspect, or extend existing ABMs – are among the relevant stakeholders; accordingly, communication must address barriers such as incomplete or lengthy documentation, complex interfaces, and abstracted processes. Despite the availability of online repositories that make ABMs accessible [Janssen 2008], many models remain underutilized after initial publication, owing to limited interoperability and the substantial effort required to understand and operate them [Thomas-Vaslin 2013, Bersini 2012]. Facilitating more effective communication is a potential solution to these challenges, as clear and accessible models are more likely to be reproduced and reused [Daly 2022].

The relevance of model communication is closely tied to the purpose of a modeling effort. There are seven primary motivations for building simulation models – prediction, explanation, description, theoretical exposition, illustration, analogy, and social learning [Edmonds 2019]. Depending on these objectives, models may be developed as explicit ‘how’ models that prioritize replicability and empirical adequacy, or as implicit ‘why’ models that emphasize inference and conceptual understanding [Epstein 2008]. This chapter concentrates on ‘how’ models, contending that their intended utility depends on clear communication with relevant stakeholders. Using a systematic scoping review of recent literature, this chapter examines the current practices for communicating ABMs to stakeholders and identify persistent gaps and opportunities to strengthen both engagement and model utility.

The remainder of this chapter is structured as follows: (1) Section 2.2, reviewing relevant state-of-the-art literature on communicating ABMs; (2) Section 2.3, detailing the approach to collect and analyze the relevant corpus; (3) Section 2.4, presenting the findings from the scoping review; (4) Section 2.5, offering insights based on the analysis; and (5) Section 2.6, summarizing the chapter’s key takeaways and implications for future research.

2.2 Related Work

Communication is a critical yet often underemphasized phase of the modeling life-cycle, as illustrated in the modeling cycle proposed by [Grimm 2005]. Within this framework, communication is not merely an end-stage activity, but a fundamental component that ensures the scientific value of a model is fully realized. Importantly, communication should be understood not only as an act but as a directional flow – from whom and to whom – which shapes how knowledge is framed and by whom it is controlled. As Arnstein’s classic “Ladder of Participation” re-

minds us [Arnstein 1969], the orientation of this flow is inseparable from issues of power: those who drive communication also drive knowledge, and ultimately, influence decision-making. A model that is not clearly and effectively communicated therefore has limited utility, particularly when the goal is to support understanding, trust, and informed decision-making among diverse stakeholders. This section synthesizes foundational studies that have shaped the discourse on communicating agent-based models, while also highlighting key limitations that motivate the current work.

One of the earliest structured efforts to assess ABM communication is the review by [Müller 2014], which critically examined the clarity and efficiency of ABM descriptions. The authors identified various categories of model documentation and underscored the lack of transparency that often impedes model evaluation, replication, and reuse. While they acknowledged the diversity of modeling contexts, they concluded that no single documentation standard suffices to meet all stakeholder and disciplinary needs. Importantly, their work laid the groundwork for understanding how communication practices intersect with the types of stakeholders engaged in ABM projects.

[Cartwright 2016] extended the debate by focusing on the communication of complex ecological models to non-technical audiences. Their study emphasized the interpretive gap between modelers and stakeholders, particularly when results are conveyed without adequate contextualization. To address this, they proposed a four-stage communication process, stressing the importance of guided interpretation to ensure that stakeholders draw appropriate conclusions from simulation outcomes. Their work underscored the importance of tailoring communication approaches to the needs and backgrounds of different stakeholder groups.

More recently, [Daly 2022] contributed to the field by reviewing progress in the standardization of ABM methodologies. While their focus was on documentation protocols and methodological rigor, rather than direct stakeholder communication, their insights remain highly relevant. They highlighted the increasing demand for transparency and structured reporting, suggesting that improved documentation can indirectly enhance communication by making models more interpretable and reproducible.

Together, these studies represent key milestones in the evolving understanding of ABM communication. However, several limitations remain. Earlier reviews, such as those by [Müller 2014] and [Cartwright 2016], predate recent advances in interactive tools, narrative generation, and AI-assisted interpretation, and lack systematic synthesis across different forms of stakeholder engagement. Additionally, few studies offer a unified framework for evaluating the effectiveness of communication strategies in ABM contexts.

Building upon these foundational works, this chapter offers an updated and systematic review of approaches for communicating ABMs to stakeholders. By mapping communication tools, participation forms, and evaluation methods across a curated corpus of literature, the aim is to identify persistent gaps and propose new opportunities for improving stakeholder understanding and engagement in agent-

based modeling.

2.3 Methodology

This review systematically assesses how ABMs have been communicated to stakeholders. It targets peer-reviewed academic publications retrieved from two major bibliographic databases – Scopus and Web of Science – using carefully constructed Boolean search strings. The search process concluded in August 2023, and the full screening and coding workflow is illustrated in Figure 2.1.

2.3.1 Search String Development

To address the question, “How are agent-based models communicated to stakeholders?”, a Boolean search query combining the terms ‘agent-based’, ‘communication’, and ‘stakeholder’ was developed. The term ‘agent-based’ was required to be followed by either ‘model’ or ‘simulation’, while ‘communication’ was expanded to include related variations. The term ‘user’ was also included as a synonym for ‘stakeholder’, based on its frequent use in the literature. The resulting search string was: *agent – based (model OR simulation) AND (communicat* AND (stakeholder OR user))*.

Additionally, ChatGPT [OpenAI 2023] was used to generate an alternative search string to enhance the breadth of literature retrieval. Prior studies have demonstrated that ChatGPT can produce high-quality Boolean queries suitable for systematic reviews [Wang 2023]. To ensure comparability with the manually crafted string, the prompt was deliberately kept simple to maintain broad applicability without introducing unnecessary complexity. Specifically, the following prompt was provided: “I want to gather a corpus for my review paper on ‘tools to communicate agent-based models to stakeholders’. Can you give me a good search string for it?”. The search string returned by ChatGPT was: *(agent – based model OR ABM) AND (communication OR visualization OR presentation) AND (tools OR methods OR techniques) AND (stakeholders OR decision – makers OR policy – makers)*.

Accordingly, two search strings – one manually constructed and one generated by ChatGPT – were entered into the databases to retrieve relevant publications.

2.3.2 Study selection

The initial search returned 335 unique articles, including 42 duplicates. Abstracts were reviewed to identify articles that specifically presented or discussed efforts to communicate ABMs to stakeholders. This screening process yielded 45 relevant articles, eight of which were retrieved using the ChatGPT-generated search string.

The excluded articles fell into several categories. First, some focused on using ABMs to simulate communication dynamics—such as peer-to-peer interactions,

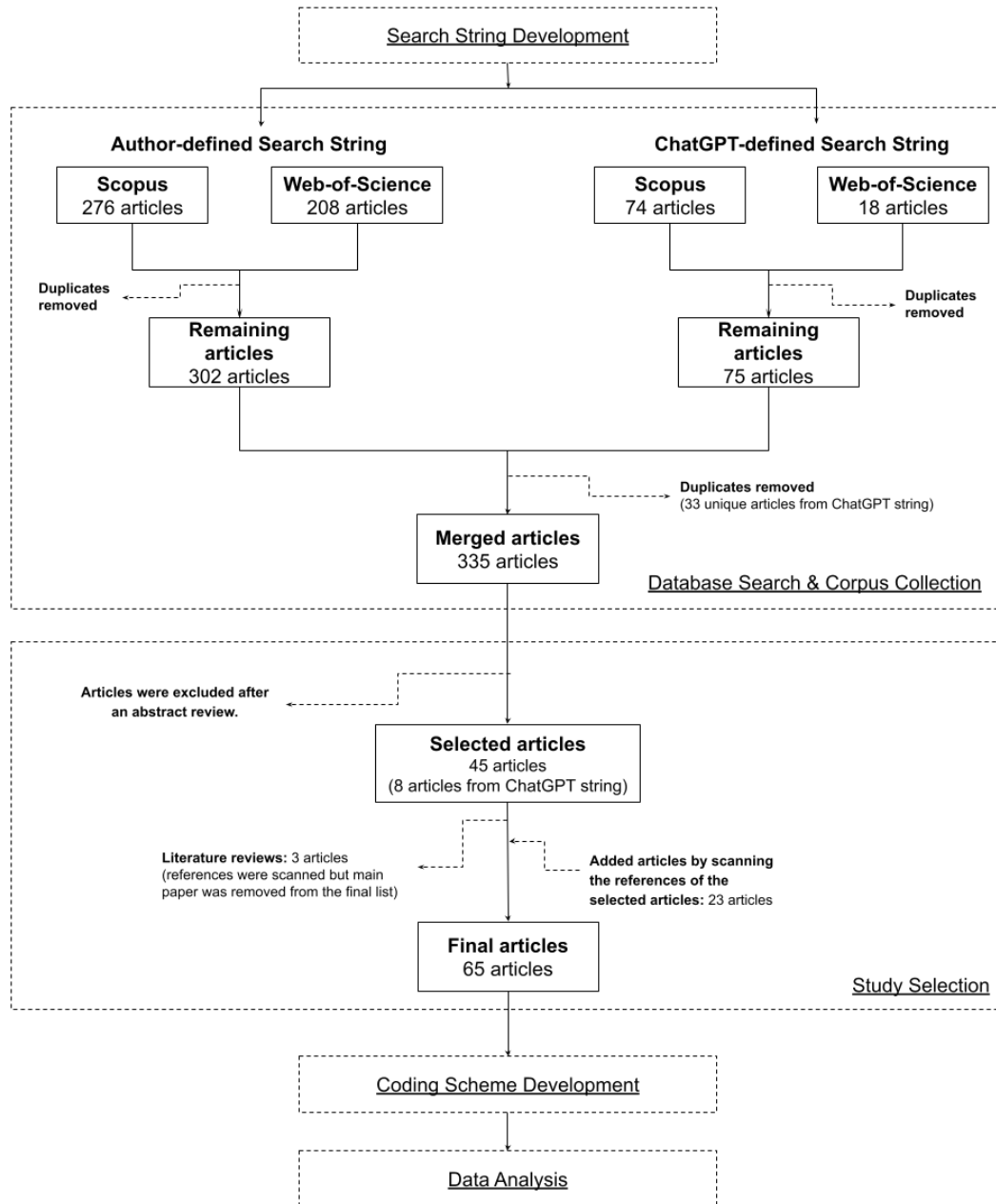


Figure 2.1: Flowchart of the complete corpus collection and review

social media behavior, crisis communication, word-of-mouth effects, political discourse, and socio-technical collaboration—rather than communicating the models themselves. Second, a subset of studies modeled communication networks (e.g., wireless networks, social networks, IoT systems), which were outside the scope of this review. Third, some articles presented ABMs or multi-agent systems without addressing communication with stakeholders. Multi-agent systems (MAS) literature was excluded because MAS research primarily concerns agent–agent communication

protocols and engineering performance [Ferber 1999], rather than the communication of model logic and emergent behavior to human stakeholders. As this review focuses on stakeholder-facing communication in ABMs, MAS studies fell outside the conceptual and methodological scope and would have introduced analytical noise without contributing to the research question.

In total, 290 articles were excluded, including 108 ABM case study articles. This high exclusion rate underscores the limited number of studies that explicitly explore how ABMs are communicated to stakeholders.

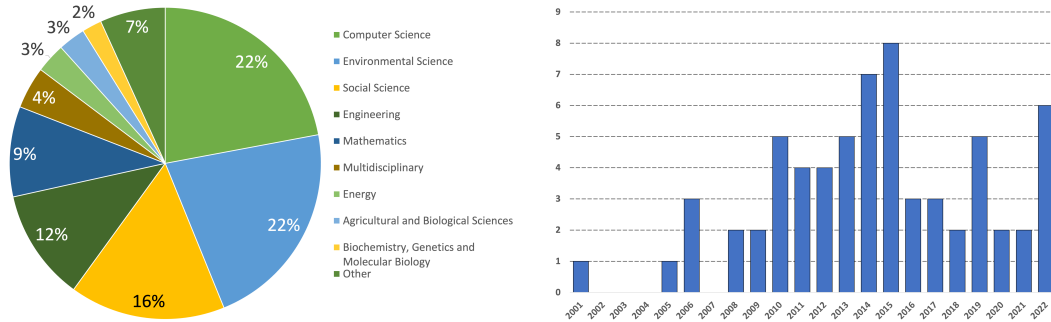


Figure 2.2: Distribution of articles: (a) by domain (left) and (b) by year (right).

After reviewing the references of the initial 45 articles and removing 3 that were found to be review articles, 23 additional articles were incorporated into the final corpus. Thus, the final corpus is composed of 65 articles that come from a diverse range of disciplines (Figure 2.2a), with nearly equal numbers from computer science and environmental science. This distribution likely reflects the fact that, while modeling has its roots in computer science, its applications are increasingly prevalent in environmental research. In this field, researchers have been progressively integrating traditional scientific methods with data science and computer science techniques [Ayllón 2021]. In terms of publication year, Figure 2.2b indicates a steady stream of contributions to the field beginning in 2008, with a notable increase in 2022 that coincides with the surge in COVID-19 modeling papers. Interestingly, research on communicating ABMs appears to have emerged more than a decade after the ABM paradigm gained prominence in the 1990s.

2.3.3 Coding Scheme Development

2.3.3.1 Sources of coding categories

The term ‘stakeholder’ follows the definition provided by [Voinov 2010], referring to individuals or groups that bear the consequences of the decisions within the simulation model. Stakeholders could represent diverse sectors, such as local and federal governments, private and public organizations, as well as individual citizens and interest groups. Their familiarity with simulation modeling could range from minimal to extensive.

Form	Top-down	Bottom-Up	Function
Nominal	Legitimation	Inclusion	Display
Instrumental	Efficiency	Cost	Means
Representative	Sustainability	Leverage	Voice
Transformative	Empowerment	Empowerment	Value (means/end)

Table 2.1: Framework for classifying Participation Form based on [White 1996] and [Van Bruggen 2019]

The review applies the Interests in Participation framework, adapted from [White 1996] and [Van Bruggen 2019] (see Table 2.1), to characterize stakeholder involvement in model communication. This framework distinguishes four participation forms – nominal, instrumental, representative, and transformative – based on stakeholders’ level of engagement and degree of control over information flow. These forms can be interpreted through three complementary perspectives:

- **Top-Down Perspective:** Participation is shaped by the project’s objectives, with stakeholders mainly providing data or receiving information from the model. In the nominal form, involvement is largely symbolic, limited to legitimizing the project. In the instrumental form, stakeholders contribute useful information during design, but their role remains restricted to data provision rather than co-design.
- **Bottom-Up Perspective:** Seen from the stakeholders’ standpoint, this perspective emphasizes their agency in shaping the model. In the representative form, stakeholders actively review, challenge, and validate the model to ensure their perspectives are reflected, making their input essential to its development.
- **Functional Perspective:** Here, participation itself becomes the project’s central function, emphasizing reciprocal learning between modelers and stakeholders. In the transformative form, stakeholders not only shape the model but also reshape their own perspectives through the process, creating a mutually transformative dynamic that drives both the project and its outcomes.

These four participation forms guided the categorization of communication instances in the reviewed articles. Nominal forms typically involved informing stakeholders about model structures and outputs. Instrumental forms focused on eliciting design input and parameters. Representative forms sought stakeholder approval or validation of the model. Transformative forms encouraged shared ownership, with stakeholders co-producing the model and integrating its insights into their own decision-making.

To identify the specific elements of ABMs conveyed during communication, the analysis drew on the works of [Macal 2010] and [Cenani 2021]. According to [Macal 2010], a typical ABM comprises three core components: agents, the

relationships between agents, and the environment in which these agents operate. Collectively, these components define the model’s overall structure. In addition, [Cenani 2021] identified two critical aspects for understanding ABM behavior: complexity and emergence. Complexity pertains to the interactions within the model, while emergence refers to the non-linear and often unpredictable phenomena that arise during simulations. The review assessed whether communication approaches supporting nominal, representative, and transformative participation effectively conveyed these essential elements – model structure, complexity, and emergent properties – to stakeholders.

To evaluate the presence or absence of communication assessments, the review adopted criteria from [Cartwright 2016], which outlines methods for assessing the effectiveness of communicating complex models and their outputs. These criteria include: (1) ‘Does the stakeholder subsequently have an improved knowledge of the model and its relevance?’; (2) ‘Does the model influence subsequent management decisions?’; and (3) ‘Does it improve the behavior of the modeled system?’ The selected articles were reviewed for any assessment attempts that aligned with these criteria. Articles involving only instrumental participation were excluded from this evaluation, as they did not correspond to any of the proposed benchmarks.

2.3.3.2 Iterative coding process

The coding scheme used to classify information from the reviewed articles was initially informed by studies discussed in the Related Work section. These studies highlighted recurring components of ABM communication, including stakeholder types, essential communication elements, and purposes for engaging stakeholders. Building on this foundation, the scheme was refined through an iterative process of open coding and constant comparison. Emergent themes were incorporated as they appeared, and coding continued until theoretical saturation was reached – that is, no new categories emerged from subsequent analysis.

As part of this refinement, the order of Participation Forms was adjusted to present instrumental before nominal forms. Both represent relatively passive stakeholder involvement, where collaboration with modelers is limited, but they differ in the depth of understanding. In instrumental participation, stakeholders contribute input during the design phase, even if communication after development remains limited. In nominal participation, by contrast, stakeholders are merely informed about outcomes without shaping the model itself. Reordering thus emphasizes a continuum of stakeholder comprehension, moving from minimal involvement toward the empowered engagement characteristic of transformative forms. Figure 2.3a illustrates this progression.

To further contextualize these forms, the modeling cycle proposed by [Grimm 2012] was used to map where stakeholder communication occurs across different phases of model development. Figure 2.3b shows how each form of participation aligns with specific stages of the cycle.

Finally, information was systematically recorded on the purposes and focus of

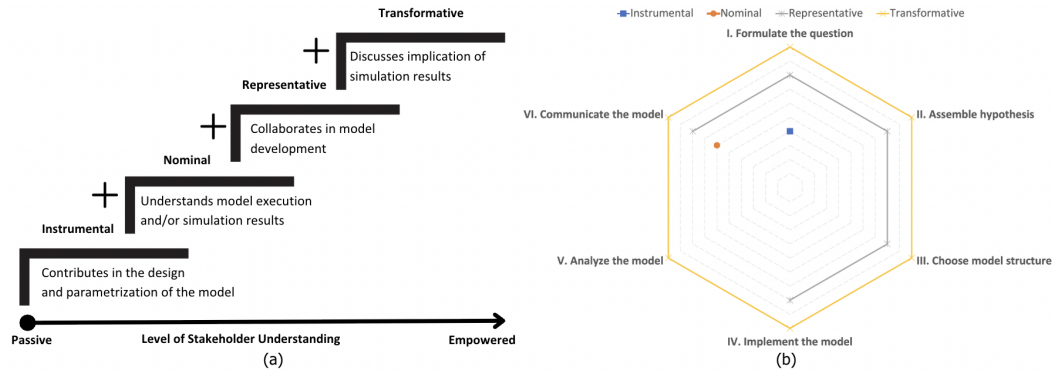


Figure 2.3: Description of the Participation Forms according to (a) level of stakeholder understanding and (b) the modeling cycle presented in [Railsback 2011]

communication approaches, along with their practical implementation. During this stage, additional categories emerged, including the specific ABM elements conveyed and whether evaluations of communication effectiveness were conducted.

2.3.3.3 Final coding scheme

The final coding scheme identifies five key components: (1) “Participation Forms”, which classify stakeholder engagement levels; (2) “Purposes and Focus of Communication Approaches”, which outline the goals of ABM communication; (3) “Communication Approaches”, which capture the types of ABM communication based on the tools used; (4) “ABM Aspects Conveyed to Stakeholders”, which identify the elements communicated to stakeholders; and (5) “Evaluation of the Effectiveness of Communicating ABM to Stakeholders”, which assesses whether communication outcomes are considered and measured. Table 2.2 presents an abridged version of the coding scheme, with complete details provided in Appendix A.

2.3.4 Data Analysis

The selected articles were analyzed through a five-phase qualitative procedure designed to systematically extract, code, and synthesize evidence on how ABMs are communicated to stakeholders. The analysis combined deductive category development, informed by prior literature, with inductive coding to capture practices emerging from the reviewed studies. The goal was to construct a comprehensive overview of existing communication practices and identify gaps and opportunities for improvement.

Phase 1 – Gathering the Data. Articles were screened and text excerpts related to communication of ABMs were extracted and annotated. The first coding pass used three *a priori* categories: types of stakeholders engaged when communicating ABMs, essential elements of effective ABM communication, and purposes for communicating ABMs to stakeholders. These categories were derived from the literature reviewed in Section 2.2 (e.g., [Müller 2014, Cartwright 2016, Daly 2022]) and

Category	Codes
Participation Forms	Nominal Instrumental Representative Transformative
Purposes and Focus of Communication Approaches	Specification Transparency Validation Presentation Reproducibility Extension
Communication Approaches	Document-type Visual Interactive
ABM Aspects conveyed to stakeholders	Structure Complexity Emergence
Evaluation of the Effectiveness of Communicating ABM to Stakeholders	With Evaluation Planned Evaluation Indirect Evaluation No Evaluation

Table 2.2: Codes used to classify the information in the relevant articles

served as sensitizing concepts guiding the initial analysis. During coding, additional patterns emerged that were not captured by the predefined structure. New categories were therefore introduced inductively, including constraints in stakeholder participation, descriptions of communication approaches, tools used for stakeholder communication, and aspects of the ABM communicated. The coding framework was iteratively refined until it adequately represented the range of communication practices reported in the literature.

Phase 2 – Sorting the Data. Annotated excerpts were compared across studies to identify recurring similarities and relationships among communication practices. This step organized the extracted material into preliminary thematic groupings that informed the subsequent coding process.

Phase 3 – Understanding the Data. Open coding was applied to the grouped excerpts to derive specific analytical codes. Coding was guided by the following analytical questions: (1) Are there commonalities across communication approaches?; (2) Which aspects of the ABM are communicated using particular tools?; (3) Which stages of the modeling process are addressed?; (4) Is the effectiveness of communication evaluated, and if so, how?

Phase 4 – Interpreting the Data. Codes were reviewed for internal consistency and definitional clarity. Each code was checked to ensure it represented a single concept and accurately reflected the meaning in the source articles. After this, the codes were finalized. Appendix A presents the descriptions of the final

codes identified during data analysis.

Phase 5 – Explaining the Data. Finally, coded findings were synthesized within each category to produce an overview of the state of the art in communicating ABMs to stakeholders. This synthesis identified dominant research emphases as well as underexplored areas requiring further investigation.

Figure 2.4 summarizes the overall analytical workflow.

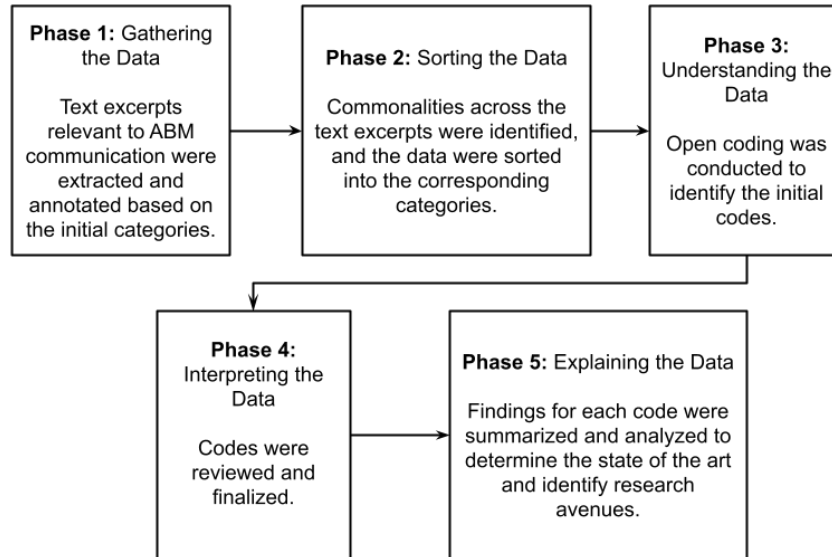


Figure 2.4: The five-phase process of qualitative data analysis adapted from [Bingham 2023]

2.4 Results

This section presents the findings of the analysis, organized into six main categories: (1) Forms of stakeholder participation, (2) Constraints in stakeholder participation, (3) Approaches to communicating ABMs to stakeholders, (4) Aspects of ABMs conveyed to stakeholders, (5) Purposes and focus of the communication approaches, and (6) Evaluation of the effectiveness of communicating ABMs to stakeholders.

2.4.1 Forms of stakeholder participation

Figure 2.5 illustrates the distribution of articles according to the forms of stakeholder participation. The analysis revealed that multiple forms of participation often coexist within a single ABM project. A total of 48 articles featured one form of participation, 9 included two forms, and 8 incorporated three forms, resulting in 90 instances of stakeholder communication across the reviewed ABM projects.

Over 40% of the reviewed articles highlighted efforts to communicate the model's structure and results to stakeholders, a practice commonly associated with nominal participation. In comparison, approximately 35% of the communication initiatives

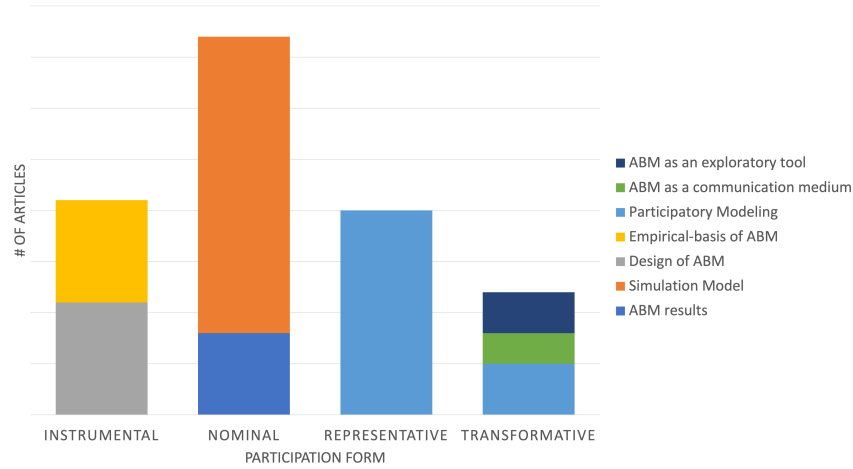


Figure 2.5: Distribution of articles by Participation Form

are focused on enhancing stakeholder representation and enabling transformative applications, while the remainder fall under instrumental participation. Although the limited number of reviewed articles makes it difficult to draw definitive conclusions about the overall state of stakeholder engagement in agent-based modeling projects, the findings reveal an increasing emphasis. While much ABM communication still centers on legitimizing models and sharing results, there is a noticeable shift toward actively involving stakeholders in the modeling process.

2.4.2 Constraints in stakeholder participation

From the papers reviewed, the following constraints and challenges emerged for each form of stakeholder participation in ABM projects.

I. Instrumental

- (a) Securing long-term stakeholder commitment proved challenging, often leading to generalized model representations due to reliance on limited stakeholder input [Pongchai Dumrongrojwatthana 2011, Forrester 2014].
- (b) Ethical considerations and the need for prolonged engagement delayed project timelines [Bharwani 2005, Roxburgh 2021].
- (c) Effective communication required a common ontology to bridge knowledge gaps across different disciplines [Cisse 2015].

II. Nominal

- (a) Models often had a steep learning curve, leading to low adoption rates [Bersini 2012, Radinsky 2017].
- (b) Stakeholder absenteeism or disinterest during presentations reduced engagement levels [Appel 2010, Gourmelon 2013, Comai 2022].

- (c) The absence of a shared language posed a barrier to understanding complex models [Onggo 2013].

III. Representative

- (a) Resource-intensive meetings and skilled facilitation were essential for meaningful engagement [Pongchai Dumrongrojwatthana 2011].
- (b) Conflicting stakeholder interests created barriers to collaboration [Naivinit 2010, Gurung 2022].
- (c) Collaboration tools often required training and a unified communication strategy [Bommel 2011, Sibertin-Blanc 2019].

IV. Transformative

- (a) Time and budget constraints limited opportunities for in-depth stakeholder interaction [Simon 2010].
- (b) Diverse stakeholder groups required tailored communication methods to ensure effective participation [Shelton 2018, Naivinit 2010].

These constraints highlight the need for improved communication tools that can facilitate stakeholder engagement while minimizing learning barriers.

2.4.3 Approaches to communicate ABMs to stakeholders

The analysis identified two primary categories of communication approaches: those supporting instrumental participation and those facilitating nominal, representative, and transformative participation. The first category is typically used during fieldwork, through individual (one-on-one) or collective (group-based) stakeholder engagement. Approaches include surveys, interviews, participatory mapping, role-playing games, and focus group discussions. The second category is further divided into three subcategories based on the type of primary tool developed for each: document-based, visual, and interactive. Figure 2.6 presents the different tools used in the second category, organized according to the type of approach.

Document-based approaches included structured tools like the ODD (Overview, Design concepts, and Details) protocol [Grimm 2006], TRACE [Ayllón 2021], and STRESS [Monks 2019], as well as unstructured descriptions of the model’s implementation. These tools were mainly used at the end of model development to communicate the finalized model.

Visual approaches comprised graphical representations like UML diagrams [Bommel 2011] and platform-specific visualizations [Taillandier 2014], which engaged stakeholders during the model design phase. They helped clarify the model’s structure and complexity but were less effective in illustrating emergent behaviors.

Interactive approaches involved gamified tools, participatory simulations, and tangible interfaces [Grignard 2018] that enabled stakeholders to engage with the model dynamically. These methods were used across all stages of development, enhancing both stakeholder understanding and model validation.

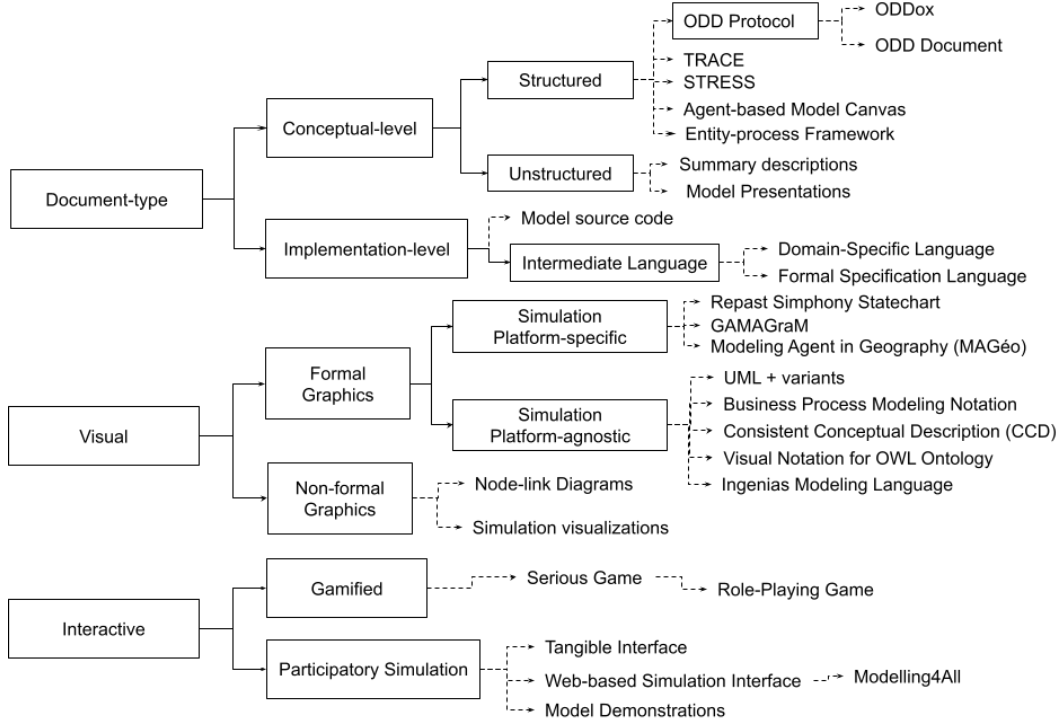


Figure 2.6: Overview of communication approaches used to facilitate Nominal, Representative, and Transformative stakeholder participation

2.4.4 Aspects of ABMs conveyed to stakeholders

The effectiveness of the communication approaches was assessed based on their ability to convey three critical aspects of ABMs: structure, complexity, and emergence. Most tools supported communication of the model’s structure and complexity, enabling stakeholders to understand how the model functions [Naivinit 2010]. However, only a few approaches adequately addressed the concept of emergence – a key feature that distinguishes ABMs from other modeling paradigms [Bonabeau 2002, Hall 2016, Adam 2018]. Table 2.3 provides a summary of the ABM aspects conveyed to stakeholders through the communication tools.

When it comes to communicating emergence, document-type approaches – such as protocols and guidelines proposed for ABM documentation – dedicate specific sections to describe the emergence observed or expected from the simulation. For example, the TRACE standard addresses emergence in the “Model analysis and application” section, the Agent-based Model Canvas (ABMC) includes it in the “Target output” section, and the ODD protocol covers it in the “Design concepts” section. Furthermore, [Grimm 2012] recommended integrating pattern-oriented modeling (POM) with ODD to improve the design and communication of emergent behaviors in ABMs. However, the STRESS-ABS guideline does not explicitly indicate where emergence should be discussed in model reports.

In terms of visual approaches, non-formal graphics, such as node-link diagrams

Tool Type	Tool	Structure	Complexity	Emergence
Document -type	ABMC	x	x	x
	TRACE Standard	x	x	x
	ODD Protocol	x	x	x
	ODdox	x	x	x
	STRESS-ABS Guideline	x	x	
	Entity-Process Framework	x	x	
	Model Source Code	x	x	
	Summary Descriptions	x	x	
	Model Presentations	x	x	
	Domain-specific Language	x	x	
	Formal-specification Language	x	x	
Visual	BPMN	x	x	
	CCD	x	x	
	Ingenias Modeling Language	x	x	
	UML	x	x	
	Visual Notation for OWL Ontology	x	x	
	GAMAGraM	x	x	
	MAGéo	x	x	
	Repast Symphony State-chart	x	x	
	Node-link Diagrams	x	x	x
	Simulation Visualization	x	x	x
Interactive	Role-Playing Game	x	x	x
	Model Demonstrations	x	x	x
	Tangible Interface	x	x	
	Web-based Simulation Interface	x	x	x

Table 2.3: Comparison of tools according to conveyed ABM aspect

[Taghikhah 2022] and simulation visualizations [Barry 2008], have been used to communicate emergence in ABMs. In contrast, formal graphics like UML do not yet support the visualization of emergent properties [Forrester 2014]. While node-link diagrams have been used to illustrate emergent properties, they were less effective than interactive simulations.

Interactive approaches have been widely used to observe emergent behaviors, particularly in ABMs designed to explore emergence. For instance, in [Yang 2022], the ABM was presented to stakeholders through demonstrations that successfully initiated group discussions on how to trigger system emergence. In another study, [Gurung 2022] engaged stakeholders in a role-playing game intended to promote the emergence of new perspectives on the modeled system. Similarly, [Carmenate 2016]

employed a web-based simulation interface that enabled stakeholders to interact with the model and observe system emergence, facilitating discussions on influencing factors and potential strategies to induce emergent behaviors. Among the three communication approaches, interactive methods appear to be the most commonly used for demonstrating emergence, as they allow stakeholders to directly observe and reflect on these patterns through participatory formats such as role-playing games or web-based interfaces.

2.4.5 Purpose and focus of the communication approaches

Thematic analysis of the corpus revealed six key objectives for model communication, based on the use of the identified communication approaches. The following section outlines these objectives and provides descriptions of each, as reported in the reviewed articles:

- **Model Specification.** Model specification reflects the researcher's understanding of the details of the target system [Pongchai Dumrongrojwatthana 2011] and should correspond to the agreed descriptions that are well understood by the stakeholders [Sibertin-Blanc 2019, Forrester 2014]. Based on the literature, model specification is particularly important when developers lack the domain expertise that informs the model, or when the model design needs to be updated due to an evolving understanding of the system [Moeiniyan Bagheri 2015]. Tools developed for communicating model specifications include visual languages [Sansores 2006, Onggo 2011, Pongchai Dumrongrojwatthana 2011], metamodels [OMG 2006, Hassan 2009, Sibertin-Blanc 2019], and formal notation [Moeiniyan Bagheri 2015].

Moreover, there has been a growing interest toward co-designing ABMs with stakeholders [Naivinit 2010, Bommel 2011, Hall 2016]. Several visual tools have been specifically developed to support this co-design process, including the ABMC [Garibay 2019], Consistent Conceptual Description (CCD) [Scherer 2013], executable UML activity diagrams [Bommel 2011], semi-formal node-link diagrams [Hall 2016, Smetschka 2020], and state-charts [Ozik 2015]. Additionally, platform-specific tools such as MAGéo [Langlois 2015] and GAMAGraM [Taillandier 2014] provide graphical interfaces that visually abstract the model code, enabling stakeholders to view the model at the level of its implementation and allowing other modelers to better interpret the code.

- **Model Validation.** ABMs are created to replicate target systems using empirical data or stakeholder insights [Hassan 2009, Forrester 2014]. To ensure accuracy, model validation is conducted by comparing simulation results to observable reality. According to [Yang 2022], model validation can be conducted in three ways: output validation, structural validation, or a combination of both [Yu 2016]. A key component of this process is stakeholder

involvement, known as “social validation” [Bommel 2011], “stakeholder validation” [Roxburgh 2021], or “truth grounding” [Forrester 2014].

Structural validation often involves stakeholder interviews, model presentations, and semi-structured questionnaires [Barbrook-Johnson 2017]. Role-playing games (RPGs) can demonstrate the ABM to stakeholders, with validation occurring in subsequent discussions [Shelton 2018], while interactive visualizations can be used to gather live user feedback [Simon 2010, Yu 2016]. Additionally, tools like UML, BPMN, CCD, metamodels, or web-based virtual labs are used to conduct collaborative evaluation [Bommel 2011, Forrester 2014, Onggo 2011, Hassan 2009, Pooyandeh 2013]. For output validation, machine learning (ML) techniques were found to be used to validate outputs of empirical models [Taghikhah 2022]. However, for models based on hypothetical scenarios it is difficult to do direct output validation [Pooyandeh 2013]. In this case, several researchers have suggested validating and calibrating the model with stakeholders [Garibay 2019, Smetschka 2020, Joffre 2015, Lotzmann 2015]. An example of this is the study by [Joffre 2015], which involves the creation of an RPG that allows stakeholders to adjust the model’s rules and parameters. This stakeholder-driven fine-tuning, in turn, helps validate that the model accurately reflects the system being modeled.

- **Model Presentation.** ABMs are often presented to disseminate the model, raise awareness of the system being modeled, and promote the application of ABMs in new domains [Pongchai Dumrongrojwatthana 2011, Ruankaew 2010, Adam 2018, Grignard 2018]. Stakeholders play a central role in these presentations [Shindler 2017], and interactive tools are widely used to present models to stakeholders (specifically, non-experts) [Gurung 2022, Grignard 2018, Adam 2019]. ABMs are frequently presented in the form of games, either as game-based versions of the target system or as gamified simulations [Ruankaew 2010, Adam 2019]. When direct stakeholder participation is not feasible, standardized descriptions like the ODD protocol [Grimm 2006] or STRESS are often employed [Monks 2019]. Additionally, visual tools such as UML and node-link diagrams are used to complement these textual descriptions [Hall 2016]. Notably, in complex and urgent scenarios, such as COVID-19 modeling, the focus shifts to presenting model results through clear visualizations and web-based interfaces [Comai 2022, Lichter 2015, Barry 2008], often without showing the underlying simulation model itself.
- **Model Transparency.** Model transparency is essential for understanding how a simulation functions and how well it represents the target system [Polhill 2009, Polhill 2015]. This becomes especially important when communicating agent-based models to stakeholders, who may view these models as ‘black boxes’ [Bommel 2011, Taghikhah 2022]. To enhance transparency, documentation frameworks such as the Entity-Process Framework

[Sibertin-Blanc 2019] and the TRACE standard [Ayllón 2021] have been developed to improve the clarity and completeness of model descriptions. In addition, reverse engineering techniques have been used to extract ontologies from agent-based models [Polhill 2009] and to automatically generate their conceptual designs [Taghikhah 2022].

- **Model Reproducibility.** Model reproducibility refers to the ability to recreate a model [Sansores 2006] and reproduce its simulation results on different platforms or by other researchers [Hassan 2009, Grimm 2012, Monks 2019]. Achieving this requires open access to the model’s source code along with non-ambiguous documentation that adheres to specific protocols [Monks 2019, Roxburgh 2021]. To support the replicability of agent-based models, the Open ABM Consortium developed an online archive for individual-based and agent-based models [Janssen 2008], featuring a ranking system that assesses models based on documentation completeness and reproducibility support. The consortium also proposed a specialized electronic journal to recognize and incentivize modelers who successfully test and reproduce models from the archive.
- **Model Extension.** Model extension refers to the ability to update or repurpose agent-based models over time. Significant effort is needed to facilitate the extension of existing models, with effective communication to future users being a crucial component. Providing comprehensive model documentation and source code, including detailed links to specific aspects of model design, is essential for helping researchers understand and build upon the model [Topping 2013]. Like in model reproducibility, the only existing effort to ensure models can be extended or built upon is the ABM archive initiated by the Open ABM Consortium [Janssen 2008]. This repository, managed by the Network for Computational Modeling in the Social and Ecological Sciences (CoMSES Net) community, currently houses over 7,500 agent-based and individual-based models, providing a solid foundation for those looking to extend and explore these models.

Figure 2.7 presents the distribution of communication approaches based on the modeling objectives they support. The following trends were identified in the analysis:

- **Model Specification:** Visual tools were most frequently used to engage stakeholders in defining and refining the model’s components, particularly when co-designing ABMs.
- **Model Validation:** Interactive methods were preferred due to their ability to involve stakeholders directly in testing and refining the model’s accuracy.
- **Model Presentation:** A balanced use of document-based, visual, and interactive approaches was observed, indicating a need for multiple strategies to reach a diverse audience.

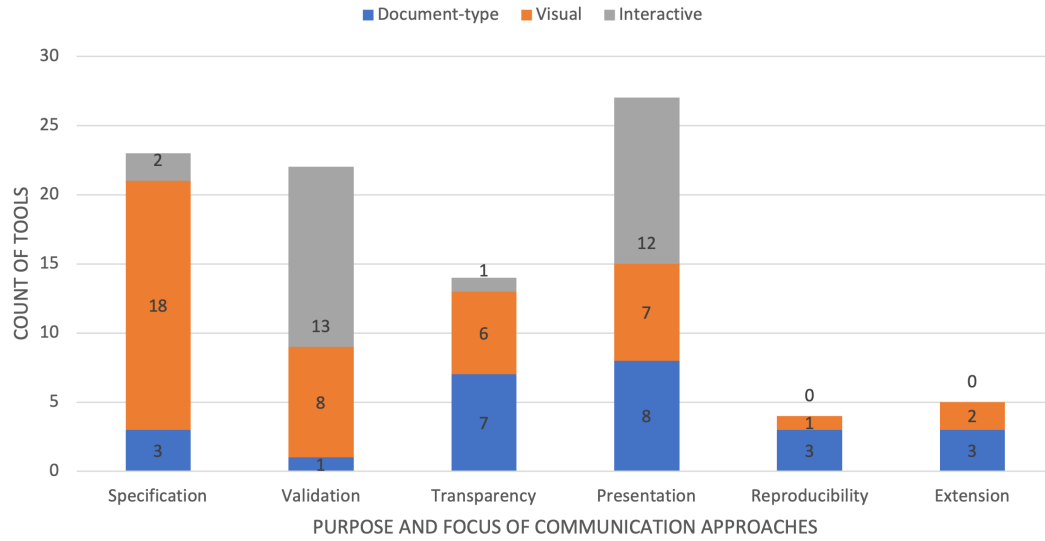


Figure 2.7: Distribution of the tools by Tool Type and Tool Purpose

- Model Transparency and Reproducibility: Document-based tools were predominant, as they provided detailed technical descriptions essential for scientific rigor.
- Model Extension: Open-source repositories and comprehensive documentation were key to facilitating the future adaptation and expansion of ABMs.

2.4.6 Evaluation of the effectiveness of communicating ABM to stakeholders

Among the 57 articles with non-instrumental stakeholder participation, only three described a direct evaluation of the communication tools' effectiveness. The assessments indicated that approaches like CCD tools [Scherer 2013], role-playing games [Joffre 2015], and node-link diagrams [Hall 2016] effectively enhanced stakeholder understanding.

Six additional articles outlined plans for future evaluations [Grimm 2012, Ayllón 2021], while 16 articles used indirect methods such as post-game debriefings [Appel 2010, Adam 2018, Gurung 2022] or open discussions to gauge stakeholder engagement [Ruankaew 2010, Gourmelon 2013]. However, the majority of the articles (56%) did not include any form of evaluation, highlighting a significant gap in the assessment of communication strategies. Figure 2.8 illustrates the distribution of articles according to the presence or absence of communication effectiveness evaluation.

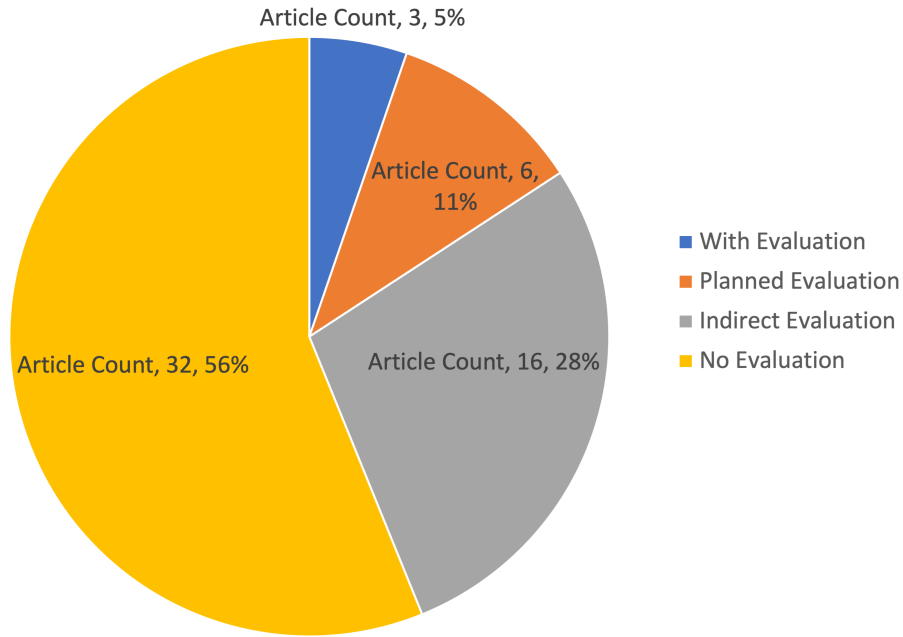


Figure 2.8: Distribution of article by type of stakeholder communication evaluation

2.5 Discussion

The analysis revealed three key gaps in the current approaches to communicating ABMs to stakeholders. These gaps highlight areas where further development and research are necessary to enhance the effectiveness and impact of ABM communication.

2.5.1 Gap 1: Focus on Communication During Development with Limited Attention to Post-Development Communication

The corpus review revealed two distinct perspectives on the focus and purpose of model communication. In the first, agent-based modeling is viewed as a participatory activity in which communication with stakeholders is central, and the process of model development is the primary product. In this view, the resulting model is often considered disposable due to its highly specific design and limited applicability beyond the original context. An example is the ABM developed by [Gurung 2022] that was used in the context of a specific conflict arising from the use of a renewable natural resource. Because the model was tailored to the specific stakeholders involved, it was treated as disposable, with communication during its development and application forming the core of the project.

The second perspective treats agent-based modeling as a scientific tool. Here, models function as part of the “materials and methods” used to generate reproducible scientific results [Monks 2019]. From this standpoint, model reproducibility is a *conditio sine qua non* for scientific rigor [Grimm 2006]. While extensive commu-

nication may not be necessary for disposable, stakeholder-driven models, scientific ABMs must be documented and communicated with future users and researchers in mind. Transparency is critical to ensure that others can replicate both the model and its results using the same materials and methods [Grimm 2012].

The majority of communication tools identified in the review focus primarily on facilitating stakeholder interaction during the model development phase. As shown in Figure 2.7, 72 communication support tools are designed for model specification, validation, and presentation, whereas only 23 aim to enhance model transparency, reproducibility, and extension. A noticeable lack of tools exists to support communication after the model has been developed and validated. This trend reflects a perspective that prioritizes immediate stakeholder engagement over the long-term usability and adaptability of ABMs.

Recommendation.

The development of communication tools tailored for post-development use of ABMs is recommended. Existing tools – such as UML diagrams and the ODD protocol – are effective during active modeling projects, where communication artifacts are generated alongside the model. However, these tools are often less useful once the modeling process is complete, particularly when limited documentation or stakeholder involvement is available.

In many cases, ABMs are published with minimal supporting materials, making them difficult to interpret, evaluate, or reuse. This highlights the need for communication tools that facilitate understanding after model development, especially for models not originally designed with long-term communication or reuse in mind.

Developing lightweight and accessible communication tools that can summarize the logic and structure of existing models in intuitive formats would address this gap. Examples include interactive visualizations, gamified interfaces, and simplified model versions hosted in public repositories. These tools would lower entry barriers for new users, enhance transparency, and promote broader engagement with ABMs across different domains.

2.5.2 Gap 2: Insufficient Communication of Emergent Behaviors Captured in ABMs

Communicating the emergent behaviors that are captured in agent-based models (ABMs) remains a significant challenge. These behaviors arise from the interactions of agents rather than being explicitly programmed, which makes them difficult both to verify and to explain. Before they can be communicated to stakeholders, it is essential to establish whether the observed emergent patterns are genuine properties of the modeled system or merely artifacts of coding errors [López-Paredes 2005]. Unlike structural components of the model, which can be validated against the conceptual design, emergent behaviors require careful analysis of simulation outcomes. The lack of clear reporting on whether such behaviors are present, absent, or relevant to the modeled system creates a gap in transparency and reduces stakeholders'

ability to fully trust the model's insights.

Emergent behavior is a key characteristic of ABMs, though not all models exhibit emergent properties. For those where emergence is relevant, effectively communicating this aspect remains a significant challenge. The review revealed that many studies (45 out of 65 articles) did not mention this in the articles. A possible explanation is that negative feedback loops, which are common in environmental models (the majority of the reviewed articles), tend to suppress significant emergent behavior, leading researchers to deem it less important to report. However, even a brief acknowledgment of whether emergence is a characteristic of the modeled system could greatly enhance stakeholders' understanding and trust in the model's outcomes.

Recommendation.

Integrating emergence-focused descriptions directly into model documentation is recommended. These descriptions should include detailed explanations of how model simulations were conducted and how results were verified to distinguish genuine emergent behavior from potential coding artifacts. Additionally, interactive demonstrations and simulations that allow stakeholders to observe and manipulate the system in real time can be highly effective for illustrating emergent behaviors and fostering deeper insights into the dynamics of the modeled system.

2.5.3 Gap 3: Lack of Systematic Evaluation of Communication Effectiveness

A significant proportion (56%) of the reviewed articles did not include an evaluation of how effective their communication efforts were in improving stakeholder understanding (see Figure 2.8). This observation aligns with [Cartwright 2016], who noted that “evaluating communication effectiveness has received little formal attention, yet the degree to which communication is effective ultimately governs the relevance and societal impact of the model”. Without systematic evaluation, it is difficult to determine which communication approaches are most successful in enhancing stakeholder engagement and model adoption. Moreover, evaluations can also reveal whether there is strong likelihood that the model and its results will be adopted and used by stakeholders.

Recommendation.

To address this gap, the development of standardized guidelines for evaluating the effectiveness of ABM communication strategies is strongly recommended. These guidelines should include the integration of evaluation frameworks into project design from the outset, enabling the measurement of stakeholder understanding and engagement throughout the modeling process. Where feasible, evaluations should involve both primary stakeholders and broader audiences to ensure comprehensive feedback [Hall 2016]. Given the lack of established guidelines for assessing ABM communication with stakeholders [Cartwright 2016], assessing stakeholders'

and new users' understanding post-development can provide valuable insights for improving long-term impact and informing the iterative refinement of models.

2.5.4 Understanding the Drivers of the Research Gaps

Several factors contribute to these gaps, including time constraints, quality of stakeholder interaction, and power dynamics within the modeling process. Time plays a crucial role in enabling stakeholders to gain a thorough understanding of the model, which ultimately enhances their confidence in its results. Limited time often restricts post-development communication efforts, which directly impacts the quality of interactions with stakeholders, particularly when it comes to explaining and validating the model's emergent behaviors. While stakeholder engagement throughout the development process is not primarily intended as a mechanism for validating emergence, it often generates this benefit indirectly: as stakeholders become more familiar with the model's assumptions, processes, and outputs, they are better positioned to assess whether simulated indicators and emergent patterns are plausible representations of the real system. This incidental validation, as observed in participatory approaches such as Companion Modeling [Étienne 2014], strengthens both the credibility of the model and the trust of its users, though such sustained engagement is not always feasible – especially when the goal is to promote the model's reuse for replication or further development. In these situations, transparency becomes essential, enabling future users to independently interpret the model's structure and outcomes.

Power dynamics, as expounded in [Arnstein 1969], also significantly influence how modeling decisions are made, the transparency of those decisions, and the evaluation process. For instance, publications on agent-based models rarely discuss the rationale behind the selection of issues to be modeled, whether those choices arise from stakeholder demand or predefined options. This lack of transparency restricts stakeholder involvement right from the beginning. Moreover, power imbalances affect both the decision to conduct communication evaluations and the selection of participants involved in these assessments. To address these gaps, a more transparent approach is needed throughout the entire modeling process, ensuring that both current and future stakeholders have the clarity required for effective model utilization and adoption.

It can be argued that the factors contributing to this gap are more anthropogenic (or, originating from human factors) than intrinsic (or, stemming from the modeling approach). Although the discussion has primarily focused on ABMs, similar challenges are evident in other modeling domains, particularly in system dynamics modeling. For instance, the application of system dynamics (SD) models in project management has often been found unsuccessful. [Größler 2007], drawing from two case studies of unsuccessful SD projects, concluded that even a well-designed SD model may yield minimal or no impact without adequate engagement from key project stakeholders. In the study by [Rumeser 2016], it was determined that the root causes of the lack of participation of stakeholders were identified as lack of

understanding and trust in the model. Among the contributing factors are (1) a short-term cost-saving mentality, which leads to using the model only once, and (2) a lack of confidence in the system dynamics model. Interestingly, the study also revealed that the lack of confidence in SD models often stems from concerns about model transparency, doubts influenced by stakeholders' prior beliefs – particularly when the model produces counterintuitive results – and political conflicts arising from competing interests.

2.6 Summary and Conclusion

Significant advancements have been made in the field of ABM, particularly in the development of approaches and tools to enhance communication with stakeholders. These efforts have improved stakeholder understanding and promoted the adoption of ABMs in various fields. However, despite these achievements, substantial gaps persist that hinder the effective communication and broader utilization of ABMs.

One key finding of this review is that most communication efforts are concentrated on engaging stakeholders during the development phase of ABMs, with considerably less emphasis on post-development dissemination and long-term usability. This limited focus on immediate stakeholders often constrains the broader adoption of ABMs and reduces their potential for reuse or adaptation in future research. Additionally, while emergent behavior is a significant feature of ABMs, it is rarely communicated effectively. This omission diminishes stakeholders' ability to fully understand the model's outcomes and their implications.

Another critical gap identified is the lack of systematic evaluation of communication strategies in terms of their effectiveness in improving stakeholder understanding and engagement. Without robust assessment protocols, it remains challenging to identify which methods foster trust and encourage the better use of ABMs among diverse audiences.

Furthermore, the complexity of ABMs presents significant challenges for stakeholders, who often have limited time to develop a comprehensive understanding of the model's functionality. The specialized language and technical nature of ABMs can create barriers for stakeholders, making it difficult to bridge the gap between the model's complexity and the stakeholders' level of expertise. To address this, it is essential to provide a diverse range of communication resources and tools – a toolbox – that present the model from multiple perspectives. Such tools would equip stakeholders with the necessary information to better understand, trust, and effectively utilize the model's outcomes. At the same time, it is important to recognize that building and maintaining such a toolbox can be highly time- and budget-intensive. The risk is that specialists may argue for the inclusion of additional components, which, while valuable, could further escalate the resource demands of the process. A pragmatic approach is therefore needed: rather than attempting to develop a comprehensive toolbox from the outset, modelers might prioritize a minimal but versatile set of communication tools tailored to the project's most critical stake-

holder needs. This staged or iterative strategy allows for the gradual expansion of the toolbox when resources permit, balancing inclusiveness with feasibility and preventing the process itself from becoming unsustainably costly.

2.6.1 Key Recommendations

Based on these findings, the following recommendations are proposed to address the identified research gaps:

- **Expand post-development communication efforts:** Develop and deploy communication tools that extend beyond the initial modeling phase to include more accessible visualizations, interactive demonstrations, and simplified summaries. These tools should be designed to engage a wide range of stakeholders, including those who may encounter the model after its initial release.
- **Highlight emergent behaviors in ABMs:** Incorporate detailed descriptions of emergent dynamics in model documentation and use interactive simulations to illustrate these behaviors in real time. This will help stakeholders better understand the interactions within the model and trust its predictive capabilities.
- **Implement standardized evaluation protocols:** Develop and standardize guidelines for evaluating the effectiveness of communication strategies in ABM projects. Integrating these evaluation frameworks into the modeling process will ensure that stakeholder feedback is systematically collected and used to improve future communication efforts.

2.6.2 Conclusion

This chapter presented a scoping review of communication strategies in ABM. Three key gaps were identified, constraining the transparency, accessibility, and practical impact of ABMs in both research and applied settings. Addressing these gaps is essential for strengthening the role of ABMs in supporting evidence-based decision-making. Improving how model outcomes and dynamics are communicated can enhance stakeholder understanding, increase trust in model results, and facilitate broader adoption across domains. Future efforts should therefore focus on developing intuitive communication tools and establishing robust evaluation frameworks that ensure ABM are clearly conveyed and its insights meaningfully interpreted.

The findings of this review provide the conceptual foundation for the next chapter (Chapter 3), which introduces ABM-VISTA, a semi-automated framework designed to enhance post-development communication and directly address several of the challenges identified in this chapter.

ABM-VISTA: A Semi-Automated Framework for Generating ABM Narratives from Simulation Logs

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In the previous chapter (Chapter 2), three main gaps in how ABMs are communicated were identified. Of these, this chapter aims to contribute to bridging Gap 1 (Section 2.5.1) – the predominant focus on communication during model development and the limited attention to post-development communication. Traditional documentation frameworks tend to emphasize design-time descriptions, but provide limited support for understanding the actual processing of models once executed. To address this, this chapter presents ABM-VISTA (Section 3.3), a semi-automated framework that improves post-development communication by transforming simulation logs into structured narratives and visual artifacts. By integrating process mining with large language models, ABM-VISTA makes the execution of ABMs

more accessible by clarifying agent behaviors, interactions, and emergent dynamics, thereby supporting clearer interpretation of how models operate. The material presented here builds on work introduced at the 11th International Congress on Environmental Modelling & Software (iEMSs 2022) and GAMA Days 2024, and is further developed in the contribution to the 26th International Workshop on Multi-Agent-Based Simulation (MABS 2025) [Arnejo 2026].

3.1 Introduction

Effective communication among model developers and stakeholders is essential in modeling and simulation [Haveman 2015]. This is particularly true for agent-based models (ABMs), where a model’s value depends on the clarity with which its design and results are described to stakeholders [Lee 2015]. Clear communication fosters better understanding, supports validation efforts, and enhances model reproducibility [Grueau 2014]. However, the diverse and inconsistent methods used to describe models – and the lack of assurance that the implementation, simulation, and results align with the description – hinder stakeholder understanding and raise concerns about model transparency [Grueau 2014]. Importantly, ABMs are characterized by complex interactions among agents that often give rise to emergent behaviors and unexpected outcomes [Bonabeau 2002]. These dynamic phenomena can remain hidden or only partially described in traditional static documentation frameworks, such as the ODD framework, which relies exclusively on exhaustive textual descriptions [Grimm 2020]. Consequently, static descriptions may overlook critical aspects of a model’s capabilities that only become apparent during execution.

Given these challenges, there is a need for innovative methods that align model descriptions with the dynamic nature of model execution while minimizing modelers’ subjective bias. An execution-focused perspective is particularly important because it captures how the model actually unfolds in practice – revealing processes, interactions, and outcomes that may remain hidden in static design-time descriptions. By analyzing models through their execution, one can obtain more faithful, transparent accounts of agent behaviors and emergent dynamics, providing a stronger basis for interpretation and communication.

This chapter introduces ABM-VISTA, a semi-automated, modular framework for generating execution-based narratives for ABMs using simulation logs and large language models (LLMs). The workflow begins with simulation runs, during which execution logs are systematically recorded. These logs then provide the basis for applying process mining techniques to discover agent workflows, which are further clarified through standardized visualizations. Finally, the resulting representations are used to guide automated narrative generation with LLMs. The key concepts and techniques underpinning this workflow are further discussed in the Related Work section (Section 3.2). This integration transforms raw simulation data into coherent visual and textual artifacts that closely mirror the model’s execution dynamics. By capturing the behaviors intrinsic to ABMs, the frame-

work not only improves transparency but also supports model verification and accessibility by providing accurate representations of simulation processes. To demonstrate its capabilities, the framework is applied to the Luneray Flu model [Taillandier 2019], available in the GAMA platform’s model library (<https://gama-platform.org/wiki/1.9.3/LuneraysFlu>). This approach represents a step toward more transparent, interpretable, and accessible ABM communication and verification. The remainder of the chapter is structured as follows: the Related Work (Section 3.2) reviews existing contributions to model descriptions in the context of model communication; the Methodology (Section 3.3) outlines the pipeline for automatically generating model descriptions using simulation traces and LLMs; the Application (Section 3.4) demonstrates the framework with a toy model; and the Discussion (Section 3.5) analyzes the findings, identifies limitations, and summarizes the contributions.

3.2 Related work

3.2.1 Model Descriptions and Communication Challenges

Model descriptions are vital artifacts in any modeling project, serving multiple purposes: they facilitate communication, deepen comprehension, enable replication, and allow comparisons with other models [Müller 2014]. The quality of these descriptions is critical to the success of a project and the usability of its outputs. However, one persistent challenge is balancing detail with readability. Comprehensive descriptions necessary for replication can be overwhelming for complex models, while overly general descriptions risk omitting critical information or creating inconsistencies with real-world systems. This balancing act remains a significant barrier to improving model descriptions for ABMs.

One promising approach to address this issue is the use of narrative explanations. In the work of [Millington 2012], narrative explanations were employed to clarify the results of generative simulation models, providing detailed accounts of key events and processes during simulations. These narratives act as intermediaries between high-level summaries of system-level patterns and formal descriptions of model structures, making them particularly useful for participatory modeling projects. Similarly, [Allison 2021] demonstrated the effectiveness of narrative explanations (or scientific storytelling) in communicating complex human-environment interactions within a transdisciplinary ABM. While these approaches show promise, current methods rely heavily on manual efforts, which are time-consuming and prone to bias and inconsistencies.

A persistent criticism of ABMs is the perception that they function as “black box” systems, leading to hesitancy among researchers and stakeholders to adopt them [Cartwright 2016, Taghikhah 2022]. While existing model documentations showed promise in addressing this issue, they often fall short due to the time-intensive nature of documentation and the risk of oversimplifying complex dynamics. This underscores the need for automated approaches to create descriptions that

are transparent, accessible to non-experts, and faithful to the model’s complexity, while minimizing the effort required for their production.

3.2.2 Process Mining

Process mining is a data-driven technique that extracts insights from event logs to analyze and enhance business processes, thereby bridging the gap between designed and executed workflows [Zacarias 2010]. Traditional process analysis methods often depend on subjective observations and interpretations, which can fail to capture the true dynamics of complex processes [Stefanini 2020]. In contrast, process mining utilizes digital event logs – comprising timestamps, activity names, and interaction details – to reconstruct actual workflows, map task executions, and analyze the discovered processes [Pan 2021a, Pan 2021b, Casaluce 2024].

Integrating process mining with simulation offers a robust approach to process analysis and optimization by extracting critical patterns from extensive datasets to create precise digital process models that enhance simulation fidelity and reliability [Pan 2021b, Kaniappan Chinnathai 2023]. This framework has been successfully applied in developing agent-based models, where process mining algorithms extract workflow blueprints from event logs [Augusto 2016, Rozinat 2009, Xu 2013]. Recent studies, such as those by [Bemthuis 2022], have further advanced this approach by leveraging agent-based models alongside process mining to uncover the behavioral rules of individual agents. Conversely, simulation models have been utilized to generate synthetic event logs, enabling controlled testing, validation, and iterative refinement of modeled processes through process mining techniques [Cimino 2025, Pan 2021b]. For instance, a study by [Sulis 2023] integrated agent-based modeling with process mining to produce synthetic datasets for a healthcare system, treating simulation outputs as event logs that were subsequently analyzed to examine hospitalization scenarios and assess activity patterns.

Although previous studies – such as those by [Bemthuis 2022] and [Sulis 2023] – have demonstrated the utility of process mining in relatively simple models, including the Schelling model and a patient care model, the scalability of these techniques to more complex systems remains uncertain. Specifically, it is unclear whether process mining can be effectively applied to enhance the transparency and accessibility of agent-based models representing complex social-ecological systems (SES). To date, no study has employed process mining to extract and communicate the processes governing individual subsystems within complex SES ABMs for stakeholder engagement. In response to this gap, the work presented in this chapter leverages process mining to advance algorithmic transparency of ABMs by using graphical representations that clarify agent behavior, towards improving the accessibility and interpretability of ABMs.

Beyond extracting workflow patterns, process mining produces tangible artifacts that make execution processes visible. The most common are process models, typically represented as directed graphs where nodes denote activities and edges capture their sequential relationships, with weights reflecting frequency of occur-

rence. These models provide a compact but expressive overview of how processes unfold in practice. In addition, formal representations, such as the Business Process Model and Notation (BPMN), can be leveraged towards a more standardized representation of the processes. Prior work has shown that BPMN diagrams can improve the interpretability and communicability of simulation models for diverse audiences, including non-technical stakeholders [Onggo 2011, Onggo 2012]. Despite their potential, such artifacts remain underutilized in the context of ABM communication. This chapter builds on these foundations by incorporating process models and BPMN diagrams into the ABM-VISTA framework to enhance transparency and accessibility of agent-based simulations.

3.2.3 Large Language Models

LLMs are advanced artificial intelligence systems designed to process and generate text in natural language. Built on neural network architectures – especially transformers – LLMs are trained on massive text corpora to learn language patterns, enabling tasks such as translation, summarization, and conversation [Lu 2024]. Their capabilities extend to natural language understanding, knowledge integration, reasoning, and even simulating aspects of human social behavior [Sun 2025], making them highly useful for exploring and modeling complex systems.

Moreover, LLMs have specifically been widely applied for narrative generation in diverse domains. In healthcare, open-source LLMs like LLaMA 3 have been used to automatically compose discharge summaries from structured clinical records, achieving notable fluency and clinical accuracy [Ganzinger 2025]. Similarly, the Generative Deep Patient model – trained on both structured and unstructured electronic health records data – demonstrated strong performance in generating clinical narratives with high clinical utility [Sivarajkumar 2025]. In finance, LLMs fine-tuned via retrieval-augmented methods have been used to automate earnings report analysis, outperforming baseline general models [Le 2024]. These applications illustrate the broad utility of LLMs in transforming structured data into compelling narratives – a capacity directly relevant to ABM communication.

In the field of Agent-Based Modeling, LLMs were used to generate dynamic agent behaviors by processing tailored prompts that incorporate environmental, social, or individual context, that can mimic flexible, human-like interactions [Lu 2024, Sun 2025, Zhan 2025]. With LLMs becoming more scalable, cost-effective, and powerful, it is more and more able to generate coherent, context-aware text that mirrors human cognition. These capabilities not only underpin the simulation of intricate decision-making processes in ABM but also facilitate communication of more complex ideas, making LLM-assisted ABM valuable in recent researches and as decision-support tools. Their multimodal integration of text, images, and video further bolsters their effectiveness in articulating nuanced concepts and detecting inconsistencies in ABM [Lu 2024, Sun 2025, Zhan 2025].

The synergy between LLMs and ABMs is particularly valuable in the study of complex systems - such as, social dynamics and epidemic spread [Han 2025,

Ren 2025]. LLMs simulate human behavior at scale, offering cost-effective insights, while ABMs provide the structured analytical frameworks needed to understand how individual interactions lead to collective outcomes [Song 2025, Zhan 2025]. This integration creates a feedback loop where enhanced LLM outputs improve ABM simulations, and insights from ABM analyses further refine LLM models.

Although recent advances have enhanced the capabilities of ABMs, a critical gap remains in how these models are communicated to stakeholders. While LLMs are increasingly used to build more expressive ABMs that capture real-world dynamics, their potential to support stakeholder-facing communication of ABMs has received far less attention. This chapter explores how LLMs can be leveraged to generate narratives that explain complex ABM processes. The goal is to bridge the persistent gap between model sophistication and stakeholder understanding.

3.3 Methodology

This section describes the overall workflow of ABM-VISTA, which stands for Agent-Based Model – Visualization & Interpretation of Simulation Traces for Accessibility, a semi-automated framework that utilizes process mining and large language models to create simulation visualizations and narrative descriptions to make ABMs transparent and accessible to stakeholders.

3.3.1 Overview of the ABM-VISTA Framework

ABM-VISTA is a modular framework composed of four key stages. The pipeline begins by logging relevant agent- and system-level information during model execution. Next, process mining techniques – specifically automated process discovery – are applied to extract model dynamics and visualize them as process maps. These maps are then refined using BPMN to clarify the sequences of actions taken by each agent type. The resulting diagrams are translated into textual summaries, which serve as prompt inputs for a LLM to generate narrative descriptions of the model’s behavior. The pipeline produces two primary artifacts: (1) process diagrams – comprising process maps (PM) and business process diagrams (BPD); and (2) a structured simulation narrative. These outputs are ultimately compiled and presented to stakeholders to support model interpretation, explanation, and communication. Each component of the ABM-VISTA framework is designed to operate independently, allowing researchers to tailor the workflow to specific models or stakeholder needs. Although the current implementation is semi-automated, the framework is built for seamless integration into fully automated pipelines and is compatible with a wide range of agent-based modeling platforms. Figure 3.1 provides a visual overview of the ABM-VISTA pipeline and its end-to-end process for generating simulation visual and narrative explanations.

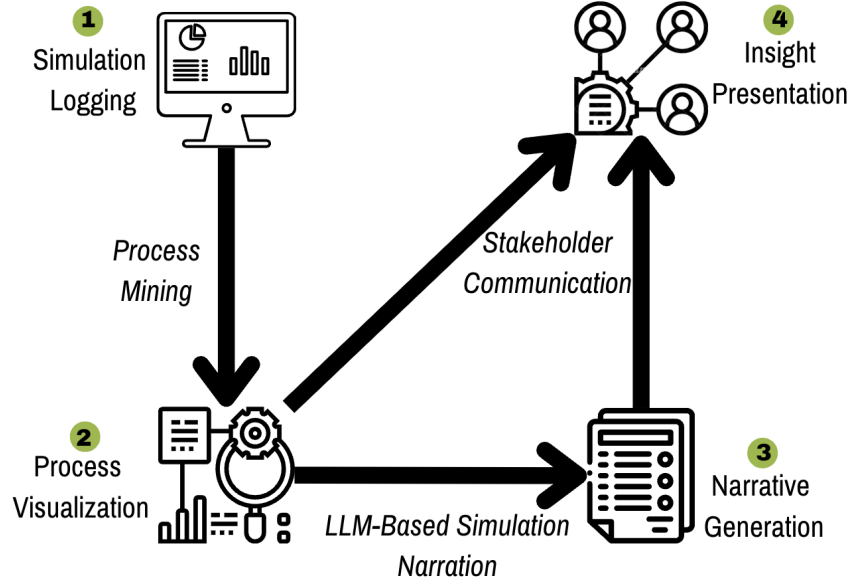


Figure 3.1: Schematic diagram of the ABM-VISTA framework, showing the overall workflow from simulation logging to process visualization and narrative generation.

3.3.2 Data Acquisition and Simulation Logging

In the ABM-VISTA framework, simulation logs provide the empirical foundation for extracting, analyzing, and communicating model dynamics. These logs are automatically captured during model execution, recording time-stamped events of actions, interactions, and state changes among agents. The level of granularity is chosen to expose the inner workings of the ABM and make interaction patterns accessible to stakeholders.

ABM-VISTA produces structured, machine-readable logs (JSON or CSV) at each simulation step, focusing on two types of information: (1) variable values that change during execution and (2) methods invoked by agents. Together, these reflect the core dynamics of the simulation: state transitions and decision points. The logging approach is platform-agnostic because the captured information – agent attributes and actions – is present in all discrete-time agent-based models, regardless of the simulation environment. In this work, ABM-VISTA is implemented in GAMA [Taillandier 2019], an open-source ABM platform with a broad model library. A dedicated extension of the GAMA debugger systematically records variables and methods at each step, exporting them into structured CSV files for process mining. This integration ensures transparency, reproducibility, and compatibility with the GAMA meta-model and GAML language [GAMA Platform 2025].

Figure 3.2 illustrates the main log fields: (1) ‘case_id’ (execution cycle or replication); (2) ‘activity’ (executed method in the format [`<type>`]`<method>`.`<agent type>`); (3) ‘time_stamp’ (simulation clock); (4) ‘value’ (current variable value); and (5) ‘resource’ (variable affected, [`Variable`]`<name>`.`<agent type>`). For method executions, the ‘value’ and ‘resource’ fields are assigned ‘nil’; for vari-

case_id	activity	time_stamp	value	resource
2	[action]description.segregation_model	01/01/1970 01:00	nil	nil
2	nil	01/01/1970 01:00	27846	[Variable]rng_usage.segregation_model
2	nil	01/01/1970 01:00	1601	[Variable]all_places.segregation_model
2	nil	01/01/1970 01:00	1601	[Variable]free_places.segregation_model
2	[action]initialize_places.segregation_model	01/01/1970 01:00	nil	nil
2	nil	01/01/1970 01:00	1120	[Variable]number_of_people.segregation_model
2	[behavior]_internal_init49.people	01/01/1970 01:00	nil	nil

Figure 3.2: Structured simulation log excerpt generated by ABM-VISTA, showing key event attributes including case ID, activity, and timestamp.

able updates, the ‘activity’ field is ‘nil’. This design follows event log standards [van der Aalst 2022b], where both ‘activity’ and ‘resource’ are retained to preserve compatibility with process mining tools and to capture complementary perspectives: what agents do and what variables change.

Beyond structure, ABM-VISTA supports both single runs and batch replications. Replications provide a generalized view of model behavior under identical parameters, while single runs may suffice for large models where memory is limited. Parameter sweeps can also be performed to explore alternative configurations, though at present their correlations with simulation outcomes are not visualized. Instead, the visual layer records whether a variable changed (changed vs. unchanged), leaving parameter–outcome integration as future work. Finally, one simulation step corresponds to a single time increment, whereas a “process occurrence” refers to the execution of a specific method or submodel. Processes may occur at every step or only under certain agent or environmental conditions, ensuring that the event stream reflects both model time and conditional dynamics.

3.3.3 Process Visualization

ABM-VISTA applies process mining techniques directly to raw event logs, transforming sequential event data into structured representations of agent behavior. Among different process mining techniques, this framework primarily utilizes process discovery. In its initial implementation, ABM-VISTA mainly relied on the Directly-Follows Graph (DFG) algorithm to generate process models, providing a straightforward yet powerful abstraction of activity sequences. In later versions, the framework was extended to also incorporate the Inductive Miner algorithm, operationalized through the `causal_net()` function in `bupaR`, enabling the discovery of more structured workflow models with explicit representations of sequences, choices, and parallelism [van der Aalst 2022a]. These visualizations facilitate the reconstruction of interpretable models that expose both recurring structures and emergent dynamics, effectively bridging raw simulation logs and communicative outputs.

The “process visualization” step in ABM-VISTA produces two complementary kinds of visual artifact: DFG-based process models (PMs) and more structured Causal Nets. In a DFG-based visualization, each unique activity is represented as a node, and a directed edge $a \rightarrow b$ is added when b directly follows a in at least one

trace; edge weights capture transition frequencies and node weights capture activity frequency [van der Aalst 2022a]. Figure 3.3A presents an example PM generated using this method.

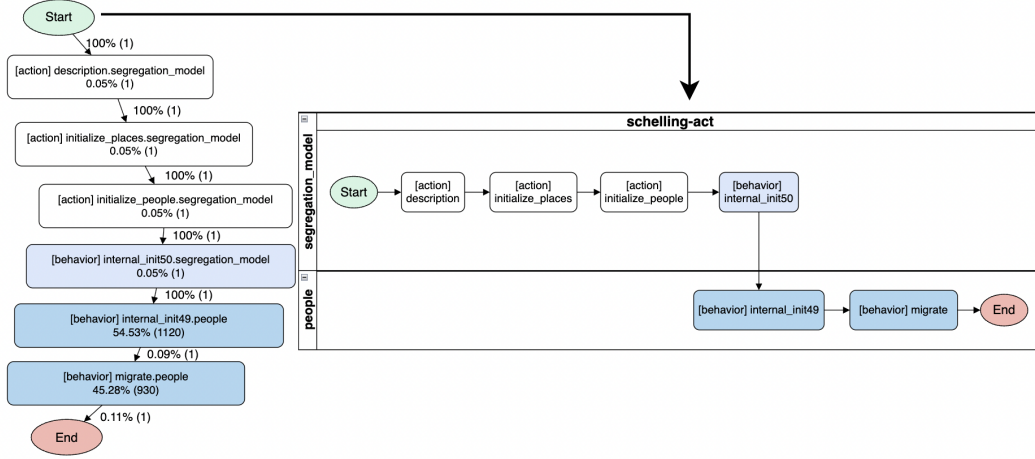


Figure 3.3: (A) PM generated using the DFG algorithm. (B) Corresponding BPD illustrating agent-environment interactions organized into lanes and pools. Note (A): node weights represent activity frequency, and edge weights represent transition frequency.

Since the log contains two kinds of information - variable and action - two kinds of PMs were also generated. To achieve this, the simulation log is divided into two sets: one, entries with a non-nil **activity** field; and, those with a non-nil **resource** field - and applying the DFG algorithm independently to each. The DFG algorithm basically states that, for each pair of consecutive, distinct events, insert a directed edge; multiple instances of that increments the edge weights. For instance, Figure 3.3A shows a transition from `[action]description.segregation_model` to `[action]initialize_places.segregation_model`, based on their sequential appearance in the log (cf. Figure 3.2). To mitigate diagram clutter and avoid spaghetti-tification, self-loops were excluded and only edges with transition weights exceeding 0.05% were retained in the final PM. The entire workflow was implemented using the *bupaR* ecosystem in R [Janssenswillen 2019], with BPMN diagrams generated from the BPMN 2.0 metamodel in *OpenBPMN* [Soika 2023] and rendered using automated layout features in *Cardanit* [ESTECO SpA 2024].

After this, ABM-VISTA translates the process models into BPDs, which are based on the BPMN standard [Chinosi 2012]. While PMs offer an efficient means of visualizing behavioral structure, BPMN adds semantic expressiveness by organizing processes into pools and lanes. In the implementation, the entire simulation is represented as a single pool, while lanes are assigned to agent types. This assignment is derived directly from the log information, where the executing agent or the variable defined as an agent attribute identifies the source of each activity. By separating methods according to the agents that execute them, the resulting

BPDs explicitly delineate roles, responsibilities, and inter-agent interactions. This integration enhances clarity by making visible not only the sequencing of actions, but also the distribution of processes across agents. The use of BPMN is motivated by prior studies showing that BPMN visualizations improve the interpretability and communicability of agent-based models, particularly for non-technical stakeholders [Onggo 2012, Onggo 2011]. Figure 3.3B illustrates a BPD derived from a corresponding PM.

Here, ABM-VISTA first generates a global PM and BPD from the complete simulation log, capturing the full range of system-level activities and interactions across all agents. To support more granular analysis, especially for inspecting individual agent behavior or agent-agent interactions, additional filtering procedures are applied. Agent-specific PMs are constructed by isolating only those log entries associated with a given agent, resulting in individualized execution traces. Similarly, agent-specific BPDs are produced by extracting the relevant elements from the global BPD, retaining only the visual components that pertain to the agent of interest. This approach enables simultaneous access to both system-wide dynamics and detailed agent-level processes, for better interpretability and communicability of the model’s internal behavior. The application of agent-specific PMs and BPDs within a case study is presented in Chapter 5, Sections 5.2.1 and 5.2.2, respectively.

3.3.4 Narrative Generation

ABM-VISTA complements process visualizations and targets to improve the communicability of simulation outputs by using large language models (LLMs) to generate narrative descriptions from simulation logs. This rationale builds on the widely recognized idea that narratives help humans make sense of complex processes by organizing events into coherent accounts [Bartalesi 2024]. As [Millington 2012] note, narratives can clarify how patterns emerge from sequences of events and interactions.

In this work, narratives are defined as textual accounts that highlight the simulation’s most important processes and variables, emphasizing sequences and interactions among agents within the model. Narratives serve as human-readable summaries of agent behaviors, state transitions, and emergent dynamics observed during model execution. Rather than fine-tuning models, the framework adopts a prompt-based approach using pre-trained LLMs, which offers flexibility across diverse simulation contexts while avoiding the computational and data overhead of supervised training. For this implementation, the 7-billion-parameter language model developed by Mistral AI [Jiang 2023] was employed.

3.3.4.1 Textual Summaries from Process Mining Diagrams

Narrative generation begins with the automatic production of textual summaries derived from process mining diagrams. These summaries are designed to remain within the token limits of LLMs, ensuring that large and complex diagrams can be

effectively processed without exceeding the model’s context window.

Rather than relying on image processing, ABM-VISTA draws on the underlying source descriptions of the diagrams – .dot files for process maps and .xml files for BPMN diagrams – which are transformed into structured, text-based accounts. Each summary conveys the main activities or variable changes, their sequential or conditional relationships, the observed frequencies or transition weights, and the roles of specific agent types as represented in BPMN lanes.

By building directly on these formal descriptions, ABM-VISTA avoids the ambiguities of diagram interpretation and ensures that textual inputs remain faithful to the underlying simulation data. This standardized translation functions as an intermediate layer between raw model outputs and narrative prompts, reducing ambiguity and enhancing the reliability and interpretability of the generated narratives.

3.3.4.2 Prompt Engineering

With textual summaries prepared, the next step was to identify how they could be most effectively integrated into the prompt structure for narrative generation. Initial attempts involved a sequence of three consecutive user prompts. The first prompt instructed the LLM to generate narratives based on descriptions of variables and processes derived from the agent-based model. The second prompt then supplied a summary of the simulation derived from a directed weighted graph, and the third prompt added the corresponding summary extracted from the business process diagram. This stepwise prompting approach ensured that the model received all relevant contextual information while still respecting input length limitations. Testing, however, revealed that the LLM struggled to retain previously provided information, underscoring the current limitations of LLMs in maintaining long-term coherence [Bartalesi 2024].

To address these constraints, the prompt type was changed from a user prompt to a system prompt, with the textual summaries appended to provide complete context. Shifting from multiple user prompts to a single system prompt was necessary because system prompts provide persistent, overarching instructions that ensure all contextual information is integrated and retained across the interaction, overcoming the limitations of user prompts, which apply only to immediate turns and often fail to preserve coherence over extended sequences [Neumann 2025]. The resulting combinations of summaries and their corresponding narrative emphases are presented in Table 3.1, which illustrates how different pairings of inputs emphasize distinct aspects of the simulation. In principle, all four representations – action log PM, action log BPD, variable log PM, and variable log BPD – could be integrated into a single prompt to produce a unified narrative. However, this option was not adopted in the present implementation. Combining all four inputs simultaneously would result in excessively long prompts, which not only increase computational costs but also risk output degradation: LLMs tend to lose focus, and misinterpret details when the input context becomes too large [Liu 2023]. To

Action Log		Variable Log		Emphasis
PM	BPD	PM	BPD	
x	x			Actions executed in the simulation and the connections between agent actions
		x	x	Agent variables that changed during the simulation and interactions between agents' attributes
x		x		Transitions in the executed methods and agent variables
	x		x	Structure of the simulation based on agent attributes and behavior

Table 3.1: Combinations of textual summaries with corresponding narrative emphasis

balance comprehensiveness with interpretability, ABM-VISTA adopts a modular strategy, integrating two complementary inputs at a time. This pairwise approach keeps queries tractable, highlights the contribution of each representation, and remains flexible enough to be extended in future work. A promising direction is the use of advanced prompt-engineering or hierarchical summarization techniques that may eventually enable all four inputs to be combined without overwhelming the model.

Based on these design choices, the final system prompt used to query the selected LLM was formulated as follows:

“You are provided with detailed descriptions of a complete simulation execution for an agent-based model. Your task is to: (1) Analyze interactions through careful examination of the interactions between processes and agents within the model; (2) Identify key transitions by highlighting crucial transitions and important paths within the simulation; and (3) Develop a comprehensive narrative that explains the overall purpose and mechanism of the agent-based model, the probable applications of the model in real-world or theoretical contexts, and the key insights and takeaways derived from the analysis of interactions and transitions. Below are the descriptions:”

3.3.5 Responsible Use of Generative Artificial Intelligence

Because AI-generated content can invite misinterpretation or misplaced confidence, particular attention was given to accuracy, transparency, and ethical use of narrative outputs. LLMs enhance the usability of simulation tools by providing natural-language explanations of complex model behaviors. However, these models are generative in nature and susceptible to hallucinations—the confident production of outputs that are factually incorrect or fabricated [Bender 2021, Maynez 2020]. This

poses a serious risk in scientific and community-based modeling, where misinterpretations can erode trust or lead to ill-informed decisions.

To mitigate this risk, all narratives produced by LLMs in this work is subject to validation for correspondence with the underlying simulation dynamics before being shared with stakeholders. Additionally, AI-generated content is clearly labeled to ensure transparency and to discourage over-reliance on automated interpretations, particularly by non-expert users. Nevertheless, the danger of hallucinated outputs remains a core limitation of LLM integration. In contexts where decisions or beliefs may be shaped by model explanations, there is a moral imperative to combine LLM assistance with domain expertise.

3.4 Application

The application of ABM-VISTA was demonstrated using a pedagogical toy model available on the GAMA platform: a simple Susceptible-Infected (SI) model that simulates the spread of flu in the city of Luneray, Normandy, France [Taillandier 2019]. In this model, people agents move between buildings via the road network, and infected individuals can transmit the flu to neighboring agents. The model’s implementation is guided by five key assumptions: (1) people move along roads from building to building; (2) they use the shortest path for their travel; (3) all individuals move at a constant speed; (4) upon arriving at a building, individuals remain there for a specified period; and (5) infected individuals are never cured. Figure 3.4 shows a screenshot of the model in execution.

3.4.1 Results

Simulation logs were collected through a batch simulation consisting of six runs, each with 600 cycles. Each run included 2,147 people agents and was executed using identical parameter settings, with log files recorded at every cycle. Logging during batch execution was chosen to obtain a simulation log that provides a representative overview of agent behavior, rather than reflecting the outcome of a single simulation instance. This approach was feasible for the toy model, as it is relatively simple and includes a manageable number of agents. In total, six log files were generated, each averaging 150 MB in size. Following automated process discovery, a PM was created from the action log files, as illustrated in Figure 3.5A. The corresponding BPD is shown in Figure 3.5B.

Since there is only one main agent type in the simulation – the people agent – the generated BPD nevertheless contains two lanes (see Figure 3.5B). The first lane, labeled `model6_model`, represents the simulation environment. In GAMA, the environment is conventionally treated as an agent named after the simulation (here, ‘model6’) with the suffix “model”. Although this world agent functions primarily as the environment rather than as an active decision-making entity, it is formally defined as an agent and thus appears as a distinct lane in the BPD. The second lane, labeled `people`, represents the only main agent type present in the simulation.

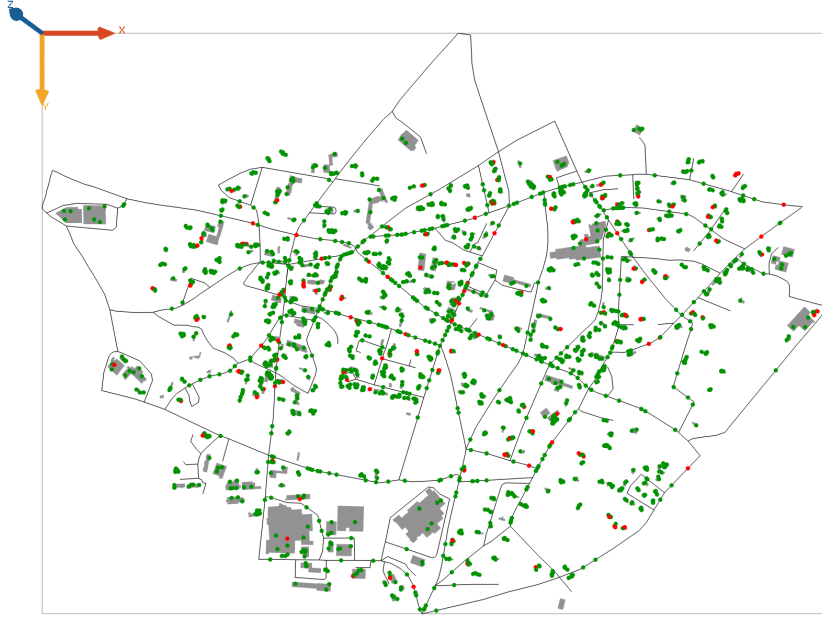


Figure 3.4: Screenshot of the Luneray Flu model during execution. Green dots represent susceptible (healthy) agents, red dots indicate infected agents, grey polygons correspond to buildings, and black lines denote roads. Agents navigate the environment following a pedestrian mobility process, which drives their movement through the spatial landscape.

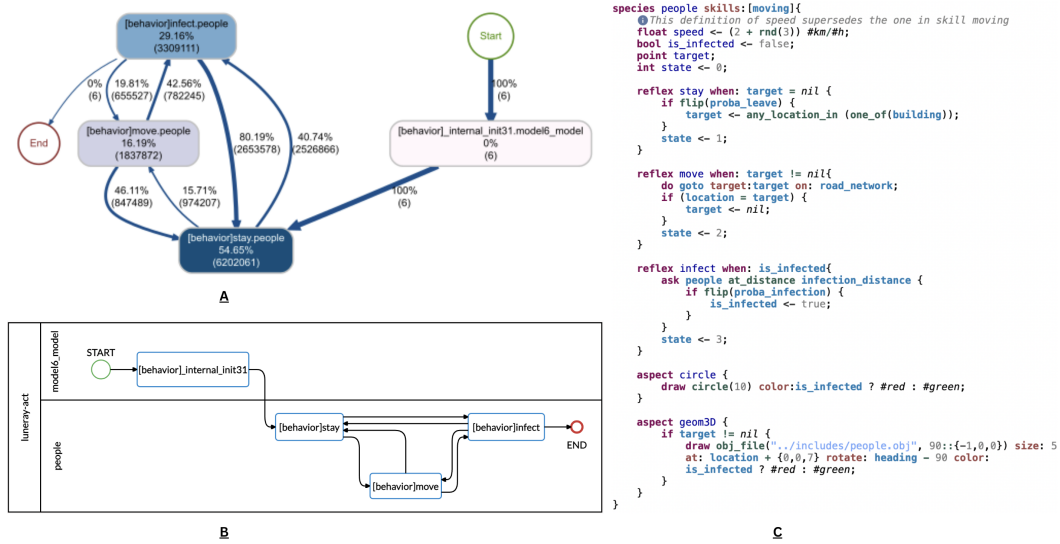


Figure 3.5: (A) PM derived from simulation action logs; (B) Corresponding BPD of A; and (C) Actual implementation code for the “people” agent type

In Figure 3.5B, the START node connects to the `[behavior]_internal_init31`

method in the `model6_model` lane, which is responsible for instantiating the agents. Following instantiation, the next method is `[behavior]stay`, indicating that the first action executed by the agents is ‘stay’. Moreover, the `infect` method is directly connected to the END node, as the log file shows that the final recorded event before termination is an infect method. To further clarify the interconnections depicted in the diagram, Figure 3.5C presents the implementation code for the people agent type.

The system then generated textual summaries of the diagrams and incorporated them into the prompt used to query the language model for narrative generation. As discussed in the previous section, the textual summaries can support multiple narrative variants. Figure 3.6 is the narrative constructed from the summaries based on the BPD and PM of the action logs.

Comprehensive Narrative
Overall Purpose and Mechanism
 The agent-based model appears to simulate the behavior of individuals (people) in response to an infectious process. The simulation begins with the START event, which triggers the `_internal_init31` task executed by `model6_model`. This initialization leads directly to the stay state for the people actor.

From the stay state, individuals can transition to either the infect or move states. The infect state represents a scenario where an individual becomes infected and has a high likelihood (0.8013) of staying in that state. However, there is also a low likelihood (0.1987) of moving from the infect state to the move state.

The move state indicates that individuals are mobile and can transition back to the infect state with a moderate likelihood (0.4369) or stay in the stay state with a similar likelihood (0.4517). The stay state allows for transitions back to either the infect or move states, with moderate and low likelihoods respectively.

Probable Applications
 This model can be applied in various real-world and theoretical contexts:

- **Epidemiology** : Simulating the spread of infectious diseases within a population.
- **Urban Planning** : Understanding how mobility patterns affect disease transmission.
- **Public Health Policy** : Evaluating the effectiveness of interventions that encourage staying at home versus moving around.

Key Insights and Takeaways

1. **Initialization Phase** : The model starts with an initialization phase (`_internal_init31`) that sets individuals to a stay state, suggesting a controlled or quarantined starting condition.
2. **Infection Dynamics** : The high likelihood of staying in the infect state indicates that once infected, individuals are likely to remain so for some time.
3. **Mobility Impact** : The moderate transition probabilities between move, stay, and infect states highlight the complex interplay between mobility and infection risk.
4. **End State** : The absence of a direct transition from infect to END (weight = 0.0) suggests that the model does not account for recovery or removal from the infectious state, which could be a limitation.

Overall, this agent-based model provides a framework for understanding how individual behaviors and transitions between states can influence the spread of an infection within a population. The insights gained can inform strategies to mitigate disease transmission by adjusting mobility patterns and intervention measures.

Figure 3.6: Generated narrative for the Luneray Flu model

3.4.2 Verification

To ensure the accuracy, reliability, and interpretive value of the artifacts produced by the framework, the evaluation followed a three-pronged verification strategy. Each component of this strategy addressed a distinct aspect of the framework’s outputs: structural fidelity, narrative quality, and behavioral alignment. Specifically, the evaluation assessed (1) the consistency between simulation logs and the generated visualizations, (2) the quality of the language model-generated narratives, and (3) the alignment between the narratives and the actual simulation dynamics.

Log–Diagram Consistency. This step served to verify the structural integrity of the visual artifacts generated from the simulation logs. Given that the framework relies on process mining to extract workflows from raw logs, it was necessary to

confirm that the resulting PMs and BPMN diagrams accurately represented the underlying simulation behavior.

To conduct this verification, the analysis involved a detailed side-by-side comparison of the information recorded in the logs and the details captured in the diagrams. The comparison revealed full alignment between the following details: methods, variables, and agent types. The only exception is the lack of loops in the diagrams which was because those loops were intentionally removed to highlight core execution paths and improve the clarity of the resultant diagrams. Excluding these intentional simplifications, the one-to-one correspondence confirmed that the process mining outputs remained reliable and structurally faithful to the original simulation dynamics.

Evaluation of LLM-Generated Narratives. Narratives represent a key output of the framework, designed to enhance the interpretability of simulation behavior – particularly for non-expert stakeholders. To evaluate narrative quality, the assessment employed the “LLM-as-a-judge” approach, in which a high-performing language model is used to evaluate the outputs of peer models. This method provides a scalable, consistent, and empirically validated alternative to human evaluation, with previous research demonstrating high agreement between language model assessments and expert judgments [Zheng 2023].

The evaluation used GPT-4 Turbo as the judging model and compared narrative outputs from three candidate models: Mistral 24B, Gemini 2.0 Flash, and Claude 3.7 Sonnet. Each model’s narrative was rated across six dimensions: precision, coverage, faithfulness, interpretive depth, novelty of insight, and clarity. Complete results and the full evaluation of the LLM-as-Judge framework are presented in the Annex C.

As shown in Figure 3.7, Gemini 2.0 Flash consistently ranked highest in overall performance, particularly in interpretive depth and clarity. Mistral 24B, however, remained highly competitive, and its open-source nature, strong accuracy, and privacy-friendly deployment make it a compelling alternative, particularly in sensitive or constrained environments.

This evaluation step confirmed that the framework can produce high-quality, insightful narratives when paired with capable LLMs and well-structured inputs derived from process mining outputs.

Simulation–Narrative Alignment. The final verification step evaluated how accurately the generated narrative reflected the actual behavior and underlying logic of the agent-based simulation. This was essential for assessing the narrative’s fidelity – not merely as a coherent summary, but as a scientifically grounded explanation of the model’s internal dynamics.

To validate this alignment, the LLM-generated narrative was compared against the output of the simulation. Based on the narrative, there are four distinct dynamic phases within the simulation:

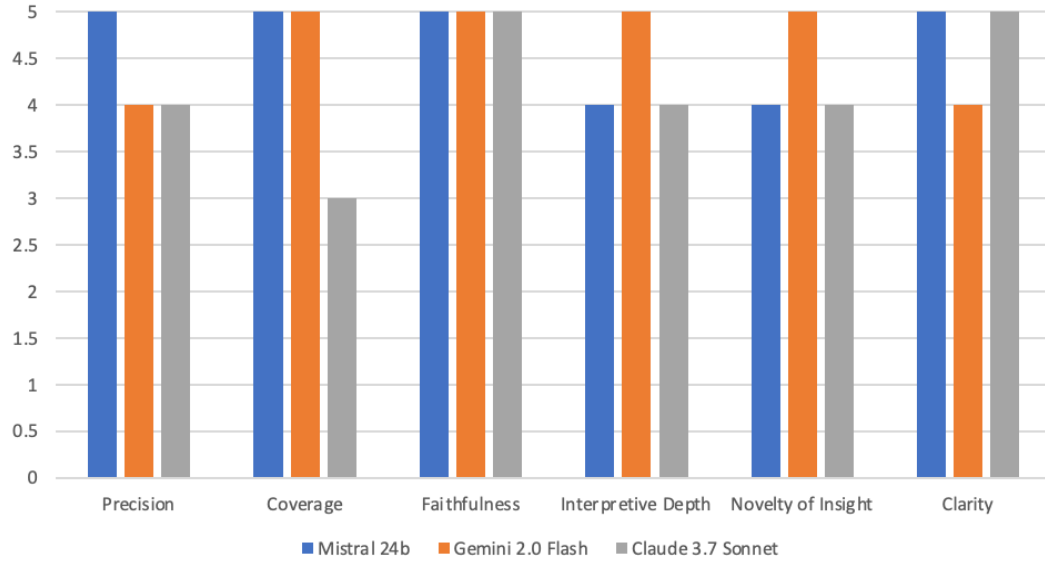


Figure 3.7: Comparative evaluation of LLM-generated narratives using GPT-4 Turbo as an automated judge, with scores averaged over three independent assessment rounds to assess the overall performance of Mistral 24B, Gemini 2.0 Flash, and Claude 3.7 Sonnet.

- **Initialization Phase (IP):** “The model starts with an initialization phase that sets individuals to a stay state, suggesting a controlled or quarantined starting condition”.
- **Infection Dynamics (ID):** “The high likelihood of staying in the infect state indicates that once infected, individuals are likely to remain so for some time”.
- **Mobility Impact (MI):** “The moderate transition probabilities between move, stay, and infect states highlight the complex interplay between mobility and infection risk”.
- **End State (ES):** “The absence of a direct transition from infect to END suggests that the model does not account for recovery or removal from the infectious state, which could be a limitation”.

These phases were substantiated by the annotated simulation output shown in Figure 3.8. The early cycles depict the IP, with most agents remaining stationary. As the simulation progresses, agents begin to move and interact (MI), triggering a rapid increase in infections (ID). Eventually, the system reaches a terminal state (ES), where all agents are infected and no further transitions occur – corroborating both the narrative and the model’s logic.

Given this alignment, it can be said that the narrative did more than recount observable events; it provided interpretive insight into the model’s structure and behavior. It highlighted key design choices (e.g., the absence of recovery), systemic

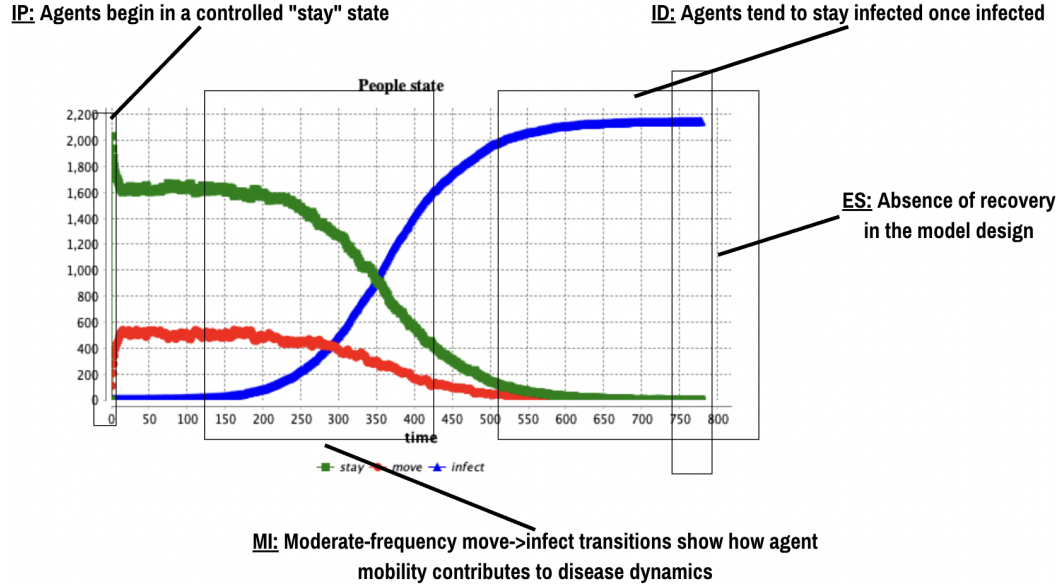


Figure 3.8: Annotated progression of agent states over time in the Luneray Flu model. The graph shows changes in population counts for each state (e.g., stay, move, infect) across simulation cycles.

mechanisms (e.g., mobility-driven spread), and emergent outcomes. These findings demonstrate that the LLM-generated narrative effectively captured both surface-level dynamics and deeper structural characteristics of the agent-based model.

3.5 Discussion

The example provided in the previous section illustrates how the framework – using simulation logs to automatically generate ABM narratives – can offer a more transparent and accessible description of an agent-based model. This framework produces three key artifacts: PM, BPD, and simulation narratives.

PMs provide an overview of how processes are executed during simulation by revealing critical methods and variables. Although clutter and information overload can be expected in visualizations of large, complex models, this issue can be mitigated by filtering nodes to include only those with weights within specific thresholds. Similarly, BPDs, derived from PMs, provide a structured view of agent interactions and relationships, aligning with the agent-based modeling paradigm. In addition to their role as standalone visual artifacts, BPDs and PMs are crucial for creating an effective prompt for the LLM. The structured and filtered representations provided by the PMs and BPDs distill the essential elements of the simulation – such as event sequences, critical transitions, and inter-agent interactions – into a concise and context-rich format. The generated narrative, which is grounded in both the implementation code and the simulation execution, complements these visualizations by offering an accessible description of the model. It helps model

users interpret the visualizations when they become overwhelming, thus providing a complementary understanding of the simulation. Together, the visualizations and the narrative form a robust foundation for a detailed description of the agent-based model, with the fully automated process significantly minimizing the effort required to produce these artifacts.

These artifacts contribute to the understanding of simulation models across diverse audiences by serving as communication tools for stakeholders, complementary documentation for modelers, and structured narratives for researchers. While currently limited to representing agent workflows based on variables and executed functions, future improvements – such as logging critical input parameters and linking them to observable outputs – could further refine their utility. Nonetheless, the integration of BPDs, PMs, and generated narratives supports model communication by providing a structured overview of processes, inter-agent interactions, and key variables, thereby enhancing the model’s transparency and accessibility. An open question, however, is how these artifacts are interpreted and acted upon by different user groups in practice. Addressing this requires participatory testing with stakeholders, an issue developed further in Chapter 6.1.

This introduction of ABM-VISTA frames the narrative generation pipeline as a reusable tool that supports better accessibility and communication of ABMs, laying the groundwork for the case-specific application described in Chapter 5.

LUNTIAN: An Agent-Based Model of an Industrial Tree Plantation for Promoting Sustainable Harvesting in the Philippines

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Designing sustainable forest management strategies requires analytical tools that integrate ecological processes with the socio-institutional realities of local contexts. The preceding chapters highlighted two complementary needs: the importance of making agent-based models more transparent and accessible to stakeholders (Chapter 2), and the development of a framework (ABM-VISTA) to support such communication (Chapter 3). To ground these discussions in practice, this chapter introduces LUNTIAN, an agent-based model developed as a case study of industrial tree plantation management in the Philippines. The model provides a concrete arena for examining how ecological dynamics – such as tree growth and

stand structure – interact with socio-economic and institutional processes, including investment behavior, labor allocation, informal harvesting, and enforcement mechanisms. By situating these processes within the University of the Philippines Los Baños Land Grant, the model not only engages with a real management context but also creates a basis for dialogue with the actors who live with, work in, and govern this landscape.

The chapter proceeds by presenting the model’s design, underlying assumptions, and methodological choices, followed by an assessment of its ability to reproduce expected dynamics and to support scenario-based exploration. The material presented here builds on research disseminated at GAMA Days 2021, the 11th International Congress on Environmental Modelling & Software (iEMSs 2022), and GAMA Days 2024, and was subsequently published in two articles in *Forests* [Arnejo 2023, Arnejo 2025b]. Together, these components establish the foundation for Chapter 5, where LUNTIAN is employed as a test case for the communication tools introduced earlier.

4.1 Introduction

Industrial tree plantations (ITPs) in the Philippines represent a strategic response to decades of deforestation and the decline in the native wood industry [Jurvélius 1997]. Historically, the country was home to over 20 million hectares of dipterocarp forests, but aggressive post-war logging and agricultural expansion rapidly diminished this vast resource, leading to significant shifts in the wood industry. Once flourishing during a “golden era” in the 1980s, the sector later faced strict regulatory restrictions and bans on natural forest extraction, prompting a pivot toward ITPs as a sustainable alternative [PCAARRD 2022].

Established under Presidential Decree No. 705, ITPs were designed to promote reforestation through long-term leases and various incentives, including low lease fees, rental exemptions, and tax breaks for qualified developers [Official Gazette of the Republic of the Philippines 1975]. This policy-driven shift was further supported by initiatives from agencies such as the Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development, which advanced ITPs as a modern approach to rehabilitating public timberlands. Additionally, government measures such as DENR Administrative Orders Nos. 01 and 41, Executive Order No. 725, and Proclamation No. 2351 aimed to streamline lease agreements, reforest degraded lands, and convert understocked areas into productive plantations, ensuring the long-term sustainability of the country’s wood industry [PCAARRD 2022].

Despite policy innovations, the ITP sector still faces persistent socio-economic, environmental, and management issues such as inequitable land tenure, resource scarcity, limited labor opportunities, and complex plantation ecosystem management [Niskanen 1996]. These issues – along with unbalanced cost–benefit sharing and unplanned land use – continue to hinder sustainable development, while envi-

ronmental degradation adds further pressure onto reforestation efforts. In addition, management challenges stemming from inadequate design, poor policy alignment, and misdirected incentives often result in non-technical failures, such as conflicts, political backlashes, and labor issues. Labor intensity remains a critical factor, and the economic viability of slower-growing native species is frequently compromised when pitted against fast-growing alternatives and even illegally harvested natural forest wood [Niskanen 1996]. As the Philippines strives to balance economic development with environmental sustainability, understanding the multifaceted challenges of ITPs is essential to shaping future policies and practices. While ITPs are sometimes critiqued for potentially undermining environmental values [Cossalter 2003, Bremer 2010], they also offer substantial social benefits – ranging from increased employment to improved rural incomes. These benefits are particularly vital as the nation continues to address persistent timber shortages through a mix of domestic innovation and reliance on imported resources.

To address these multifaceted challenges, this chapter examines the following: *Can industrial tree plantations be designed and managed in ways that balance economic viability, ecological restoration, and social inclusion?* This question demands a system-level approach that integrates human and ecological dynamics over time. Viewing an ITP as a social-ecological system (SES) allows us to consider the feedback among stakeholder decisions, forest conditions, and institutional mechanisms. In this context, a simulation-based approach – particularly agent-based modeling – is well suited for testing management scenarios under realistic constraints by representing diverse stakeholders (e.g., investors, laborers, and managers) as autonomous agents whose behaviors are shaped by rules, preferences, and dynamic environmental conditions. To this end, this chapter introduces LUNTIAN, an agent-based model developed to simulate an experimental ITP within a mountain forest managed by the University of the Philippines Los Baños Land Grant Management Office. Framed as an SES, LUNTIAN seeks to strike a balance between two primary objectives: preserving forest cover and ensuring the long-term profitability of ITP operations for both investors and local communities.

Unlike established forest models such as 3PG [Landsberg 1997] and FORMIND [Köhler 1998], which concentrate almost exclusively on biophysical processes such as tree growth, competition, and stand dynamics, LUNTIAN places socio-economic dynamics at the core of its simulation. It actively models labor decisions, informal harvesting behavior, and investment processes – critical human factors that traditional forestry simulations often treat as external or overlook entirely. While spatial forest-landscape models such as LANDIS [Mladenoff 2004] have made strides in incorporating management-driven change by simulating disturbance regimes and policy interventions, they typically treat socio-economic factors as external inputs or future integration points rather than intrinsic system components. LUNTIAN distinguishes itself by employing an agent-based architecture that directly simulates the decisions, behaviors, and feedback loops of key human actors – including investors, laborers, and enforcement agents – within the forest ecosystem. This design embeds socio-economic processes as internal, dynamic elements of the sys-

tem, enabling LUNTIAN to evaluate sustainability in a more holistic and integrated manner across ecological, economic, and social dimensions.

The remainder of this chapter is structured as follows. Section 4.2 outlines the methodological framework employed to develop and evaluate the LUNTIAN model, including the case study context, model design, and assessment procedures. Section 4.3 presents the simulation results, encompassing forest dynamics, model alignment, sensitivity analysis, and scenario-based optimization. Finally, Section 4.4 discusses the broader implications for sustainable ITP management and highlights key limitations and avenues for future research.

4.2 Materials and Methods

This section presents the methodological framework used to develop and assess the LUNTIAN agent-based model. It begins with a description of the case study area and the social–ecological context that informed the model’s design. The rationale for adopting an agent-based modeling (ABM) approach is then provided, as well as the ethical dimensions of the model design and stakeholder engagement. The model’s structure is subsequently outlined using the ODD (Overview, Design Concepts, and Details) protocol, including agent definitions, scheduling logic, and key submodels. Finally, the section details the methods employed for model validation, sensitivity analysis, and scenario exploration.

4.2.1 Description of the Case Study

4.2.1.1 Study site.

The study site is located inside the University of the Philippines Laguna Land Grant (UP LLG) – at 14° 23' N, 121° 29' E. It is one of the two land grants in the southern portion of the Sierra Madre Mountain Range in the Luzon Island of the Philippines, awarded to UP through Republic Act 3990 dated 18 June 1964 and confirmed through Special Patent No. 532 and Original Certificate of Title P-919 issued 8 August 1965 [University of the Philippines 2012]. Figure 4.1A shows the location of the ITP area in relation to Laguna de Bay, while Figure 4.1B shows its location within the entire UP LLG site.

The biophysical environment of the study site consists of hilly to mountainous terrain with a mix of forest cover types. Baseline figures for tree distribution were drawn from a 2019 forest inventory conducted within the gray-shaded portion of the UP LLG shown in Figure 4.1B. These data were obtained directly from the UPLB Land Grant Management Office [UPLB Land Grant Management Office 2019]. The inventory was based on ten transects within that area and does not represent the entire land grant; to date, no comprehensive forest inventory is available for the full extent of the UP LLG. Within the surveyed portion, 48 species were recorded, 45 native and 3 naturalized, with native trees constituting approximately 99% of the recorded population, underscoring the ecological integrity and semi-

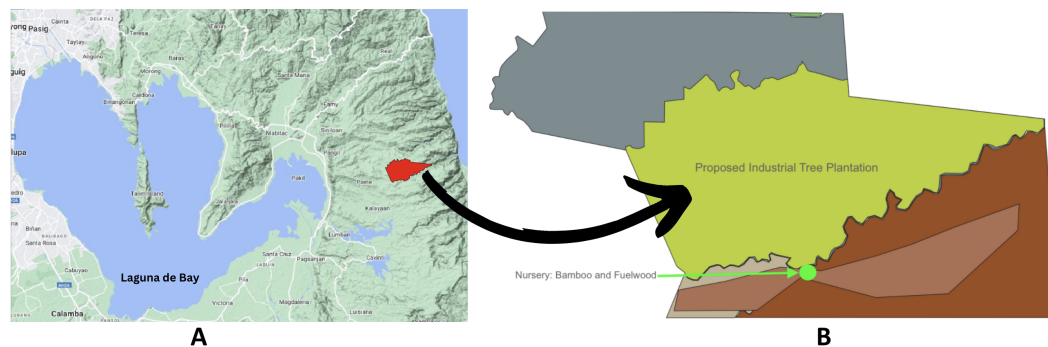


Figure 4.1: Location of the case study site

natural character of the inventoried area. Among the native species, members of the Dipterocarpaceae family – such as *Anisoptera thurifera* (locally known as Palosapis) – are dominant, accounting for over 34% of the native tree population. The remaining 1% comprises naturalized species, most notably *Swietenia macrophylla* (Mahogany), which is represented by three individuals in the inventory. This represents a marginal fraction of the tree population in the surveyed area, highlighting Mahogany’s limited ecological footprint. These naturalized individuals may be present due to earlier planting activities or unintentional spread.

4.2.1.2 Social Issue

The evolution of the UP LLG’s ownership and management reflects a series of strategic shifts over several decades. On June 4, 1953, the Secretary of Agriculture and Natural Resources initiated this process by issuing Timber License Agreement No. 27-A to International Hardwood and Veneer Company of the Philippines (Interwood), granting them exclusive rights to harvest timber – a license that was renewed in 1961. Later that year, on September 25, Proclamation No. 791 withdrew this parcel of public land from sale, reserving it for the College of Agriculture at the University of the Philippines. This reservation was cemented on June 18, 1964, when Republic Act 3990 ceded 3,435.4 hectares in full ownership to the University of the Philippines, with the intention of establishing a central experiment station to advance research and extension functions across the Colleges of Agriculture, Arts and Sciences, and Veterinary Medicine [Supreme Court of the Philippines 1991]. From 1964 until 1989, the University of the Philippines (UP) Diliman managed the land grant, and between 1984 and 1989, UP Diliman also contracted with the National Development Corporation to oversee logging operations. In 1989, management was transferred to the College of Agriculture at UPLB, and by 1992, it was restructured under the Office of the Vice-Chancellor for Planning and Development, which then includes the Land Grant Management Office (UPLB-LGMO) [Office of the Secretary of the University 2010]. Presently, the UP LLG is managed by the UPLB-LGMO.

Among current initiatives, the ITP has emerged as a promising strategy for

generating income through managed timber harvests while maintaining ecological integrity [University of the Philippines 2012], and approximately 1,411 hectares of the 3,435.4-hectare site has been allocated for this project. Given its proximity to local communities, the ITP also presents an opportunity to promote employment and rural development, highlighting the importance of integrating social considerations into ITP design and management.

These social considerations are especially relevant given the evolving land-use dynamics surrounding the UP LLG. In 2020, Barangay San Antonio – the closest barangay (the smallest administrative division in the Philippines, similar to a village or district) – had a population of 11,263 individuals distributed across multiple sitios (smaller hamlets or sub-village units within a barangay) [Philippine Statistics Authority 2020]. A field visit in January 2023 revealed that these sitios developed gradually over time, with the most recent, Sitio Balatkahoy, established about two decades ago near the proposed edge of the ITP area. Sitio Balatkahoy has since become a focal point of land-use contention. In 2020, the Department of Agrarian Reform (DAR) flagged the land grant as potentially eligible for redistribution under the Comprehensive Agrarian Reform Program (CARP), raising questions about the future of land designated for academic purposes [Manila Bulletin 2020]. A subsequent UPLB Legal Office site inspection in 2023 confirmed the presence of informal settlers, underscoring the complex challenges of undocumented occupancy and overlapping claims [UPLB Legal Office 2023]. Once sparsely populated, the area has experienced increased in-migration driven by economic activity and shifting land use – from timber extraction to academic and plantation development.



Figure 4.2: Interview with Bantay Bayan (citizen patrol), Elder, and Residents

4.2.1.3 Forest Management Choice

In this study, the forest management system is modeled as a SES, following Ostrom’s definition [Ostrom 2009], where the university, investors, and laborers are

considered users (or actors) and institutional components are represented by the rules governing harvesting and investment. The roles of various entities – including the university as resource manager, tree growth dynamics, planting and harvesting activities, investors, and community stakeholders – are explicitly integrated to reflect the complex interactions that characterize the UP LLG. This conceptualization is informed by a site visit conducted in January 2023, which provided valuable insights into on-the-ground realities, stakeholder dynamics, and operational practices (see Figure 4.3). All stakeholder engagement procedures described in this chapter followed ethical protocols for informed consent and data confidentiality.



Figure 4.3: On-the-ground conditions observed during the January 2023 site visit to the UP LLG. The images highlight key infrastructure inside the UP LLG area. Clockwise from top left: (1) a bunkhouse under construction intended to accommodate laborers and visitors; (2) a temporary settlement not belonging to the university; (3) makeshift houses for laborers near operational zones; (4) a university-managed nursery with seedlings for enrichment planting; and (5) a guard post serving as a security checkpoint and temporary housing for special police and forest rangers.

Human resource dynamics are central to the sustainability of the ITP and are closely linked to investment decisions. The model follows the university’s implementation plan: private logging is excluded, and community members are hired as formal laborers for nursery maintenance, planting, and harvesting. Employment is offered based on investment-driven demand; thus, the number of active investors directly affects labor opportunities. When labor demand is unmet or when working conditions are perceived as unfavorable, some individuals may turn to unauthorized independent harvesting. This dynamic reflects real-world tensions between job scarcity and informal forest use. Figure 4.4 illustrates the institutional relationships and resource utilization links among the key actors in the ITP system, with a focus on how the university mediates interactions among investors, community

labor, and the forest landscape.

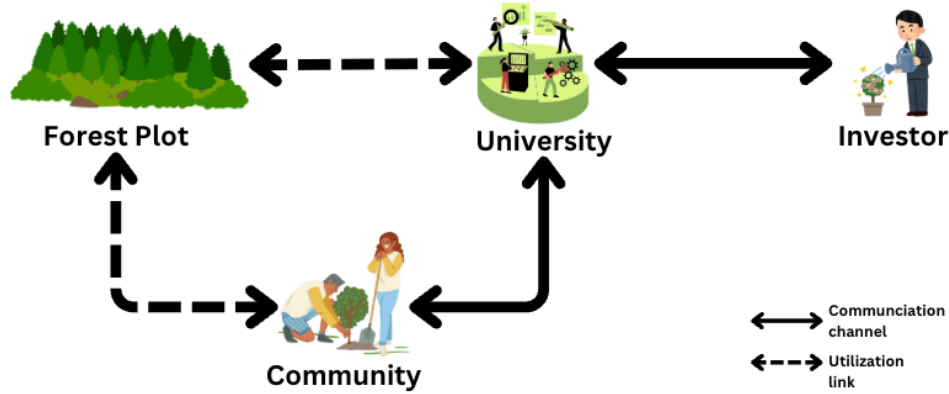


Figure 4.4: Schematic representation of key actor interactions within the ITP system. Solid arrows indicate communication channels, while dashed arrows represent utilization or resource exchange links. The diagram highlights how the university serves as an intermediary between investors and local community members, allocating labor and coordinating plantation activities. Labor availability and forest use are shaped by these institutional relationships and influence both formal employment and potential unauthorized harvesting behavior. Icons by various contributors via Canva.com (Free Content License). Figure created by the author.

A key component of the plantation strategy involves nursery management, which supports regeneration by maintaining a steady supply of seedlings – particularly native species – for enrichment planting. Managed by the university, nurseries serve as propagation hubs where community laborers are hired to collect wild seedlings, nurture them in controlled plots, and prepare them for transplanting into investment areas. The nursery system not only sustains replanting cycles but also plays a vital role in reinforcing species selection strategies aimed at balancing ecological integrity and economic viability.

Species selection, therefore, is tightly linked to nursery operations and broader management practices. The UP LLG hosts a mix of native and exotic species, as documented in a 2019 forest inventory. In operational contexts, fast-growing exotics such as *S. macrophylla* are often favored for their quicker economic returns. However, native species – particularly from the Dipterocarpaceae family – are more ecologically beneficial, contributing to biodiversity and long-term resilience. This study incorporates both groups to reflect these trade-offs. The selection was shaped by three constraints: (1) limited availability of species-specific growth data, (2) the need for manageable and interpretable scenario comparisons, and (3) a focus on testing strategic trade-offs over replicating full silvicultural complexity. This approach reflects the university’s implementation strategy and supports evidence-based exploration of sustainable plantation configurations.

4.2.2 Justification for an Agent-Based Modeling Approach

SEs exhibit complex and dynamic behavior, driven by the co-evolving interactions between human societies and natural environments [Gonzalez-Redin 2024, Nugroho 2023]. In these systems, human decisions and ecological processes influence one another across multiple spatial and temporal scales. ITPs represent a specialized form of SE by combining biological growth, competitive tree dynamics, and intensive management to pursue both economic and ecological goals [Newnham 1964, Liu 1995].

Researchers have long used simulation models to understand SEs. For instance [Newnham 1964], developed an individual-based growth–yield model capable of simulating decades of forest development in minutes, while [Liu 1995] introduced spatially explicit models that captured forest succession and competitive dynamics. Building on these foundational efforts, ABMs have emerged as powerful approaches to representing individual-level behavior in SEs, revealing system-level patterns – such as resilience and regime shifts – that arise from local interactions [Bitterman 2016, Bartkowski 2020]. Despite the strengths of these models, researchers have seldom applied ABMs to forest-based systems – particularly within industrial plantations – even though these models are well suited for simulating the interplay of stakeholder behavior, environmental feedback, and institutional policies in ITP contexts [Newnham 1964, Liu 1995, Bitterman 2016]. For example, [Bartkowski 2020] demonstrated how ABMs, when combined with land-use optimization, can assess the ecological and economic feasibility of sustainable resource use. Meanwhile, most existing forest models continue to emphasize biophysical processes while underrepresenting socio-economic factors such as investment decisions, labor dynamics, and enforcement mechanisms [Newnham 1964, Liu 1995]. Recent applications, such as [Gonzalez-Redin 2020] on palm oil landscapes, show that ABMs can effectively capture complex decision making and policy interactions in managed systems. Furthermore, a review by [Nugroho 2023] confirms that ABMs and system dynamic models remain underutilized in intensively managed settings such as ITPs. These gaps underscore the need for models that integrate detailed ecological processes with agent-level decision making to enable hypothesis testing, scenario exploration, and the design of more adaptive and sustainable management strategies.

Unlike aggregate models that rely on probabilistic assumptions, ABMs allow for the fine-grained representation of actor heterogeneity and dynamic role switching [An 2012], such as laborers becoming informal harvesters in response to limited employment opportunities. These transitions are not isolated decisions – they are part of feedback loops, where institutional rules, economic incentives, and enforcement presence shape behavior over time. For instance, persistent unemployment can lead to increased unauthorized harvesting, which in turn triggers enforcement responses and alters labor dynamics in future cycles. Such interdependent processes are difficult to simulate realistically using non-agent methods without significant abstraction or loss of spatial and behavioral resolution. Capturing this localized,

emergent feedback is key to understanding the full complexity of social–ecological systems.

This study adopts an agent-based modeling approach to simulate the dynamics of ITPs. ABMs provide a scientifically rigorous framework for evaluating long-term management strategies under uncertain environmental and socio-economic conditions. This bottom-up structure enables the representation of behavioral diversity (e.g., passive versus risk-seeking investors), the simulation of feedback loops (e.g., labor competition leading to informal harvesting), the testing of interventions (e.g., incentives or enforcement mechanisms), and the observation of emergent outcomes that may not be captured by traditional models. By accounting for these interdependencies, the ABM facilitates systematic analysis of ecological, economic, and social outcomes. Specifically, it is used to examine how harvesting intensity, species composition, and community engagement influence forest cover, biodiversity, and financial returns. Furthermore, the model supports evidence-based decision-making by providing interpretable metrics – such as projected net earnings, forest regeneration, and employment outcomes – across a range of management scenarios. Rather than relying on static assumptions or aggregate averages, the model simulates and compares specific strategies to identify those most aligned with sustainability goals.

4.2.3 Ethical Dimensions of Model Design and Stakeholder Engagement

The development and use of ABMs in social-ecological systems necessitate careful consideration of how model assumptions, stakeholder roles, and system representations are constructed. ABMs, by design, encode simplifications and formal rules that reflect the modeler’s framing of reality. This introduces the risk of epistemic bias, especially in projects where stakeholders differ in power, access, or technical literacy [Saltelli 2020]. In the LUNTIAN model, stakeholder interviews and participatory workshops were conducted to mitigate this bias and ensure that localized knowledge informed model rules and parameterization. Still, full representativeness remains challenging, and reflexivity about whose perspectives are privileged is essential throughout the modeling process [Lee 2015].

Stakeholder engagement further raises ethical obligations around informed consent and participation equity. During the conduct of this study, participants were briefed in accessible language on the goals of the interview, the use of their input, and their ability to opt out at any point. Their contributions were anonymized and handled confidentially, following standard research ethics principles [Israel 2006]. The study also recognizes that stakeholder engagement should not be extractive — local communities should benefit from the tools they help shape. Therefore, the outputs of the LUNTIAN model and the ABM-VISTA framework were designed to remain usable and interpretable beyond the lifespan of this research.

Finally, while ABMs are increasingly used for scenario exploration and policy analysis, their results can be misused if interpreted as predictive or prescriptive. The LUNTIAN model is not intended to make deterministic forecasts, but to sup-

port dialogue and reflection among stakeholders. Communication materials were developed with this distinction in mind, and the limits of the model were conveyed clearly in both written and verbal outputs.

4.2.4 Description of the ABM

This section describes the ABM using the Overview, Design Concepts, and Details (ODD) protocol [Grimm 2006, Grimm 2012], a standardized framework for documenting agent-based models. The Overview section outlines the model’s purpose, entities, spatial and temporal scales, and simulation schedule. The Design Concepts section presents the core behavioral assumptions and theoretical principles embedded within the model. Lastly, the Details section provides a description of the implementation of the model’s subcomponents and the simulation scenarios used in the analysis.

4.2.4.1 Overview

LUNTIAN is a spatially explicit agent-based model developed to simulate an industrial tree plantation within the UP LLG. Built on the GAMA platform (version 1.9.3) [Taillandier 2019], it integrates empirical data and stakeholder input to explore management strategies that balance ecological regeneration, financial viability, and community engagement. The model captures interactions among key actors (university, investors, laborers, and community members) and biophysical processes such as tree growth, hydrology, and land-use change.

Purpose. The LUNTIAN model (Labor–UNiversity–Timber Investment–Agent-based Nexus) is an agent-based decision-support tool designed to evaluate the sustainability of ITP implementation in the Philippine context. The name also draws from the Filipino word *luntian*, meaning “green,” to emphasize the model’s commitment to ecological restoration. The model simulates interactions among ecological processes, labor dynamics, institutional constraints, and investment decisions to explore plantation management strategies under conditions where field experimentation is limited. Grounded in the objectives of the UP LLG, LUNTIAN does not attempt to resolve land tenure or political conflicts; instead, it quantifies ecological, economic, and social trade-offs within a defined operational framework. Specifically, the model explores variations in ITP implementation parameters to assess whether introducing native tree species into plantation systems dominated by exotic species can improve sustainability outcomes, and how different native–exotic planting mixes affect long-term ecological recovery and economic performance. The model is aimed to answer the question: “Can the ITP be implemented sustainably, and if so, what are the optimal parameters to maximize returns?” This research was motivated by concerns raised by forestry practitioners regarding the long-term sustainability of current plantation practices and was conducted as part of a doctoral research; while the study itself was not directly commissioned or institutionally funded, it

was supported through a PhD fellowship grant.

Entities and State variables. Two main agent types – biophysical and social – interact within the simulated ITP environment to represent the system’s ecological and institutional dynamics. Each agent is characterized by internal state variables – such as employment status, investment history, and patrol assignment – that influence its behavior and interactions over time. These variables are informed by empirical data, the literature, and stakeholder input, and are operationalized through submodules described in later sections. Figure 4.5 presents the model’s core entities and their interrelationships in a UML class diagram.

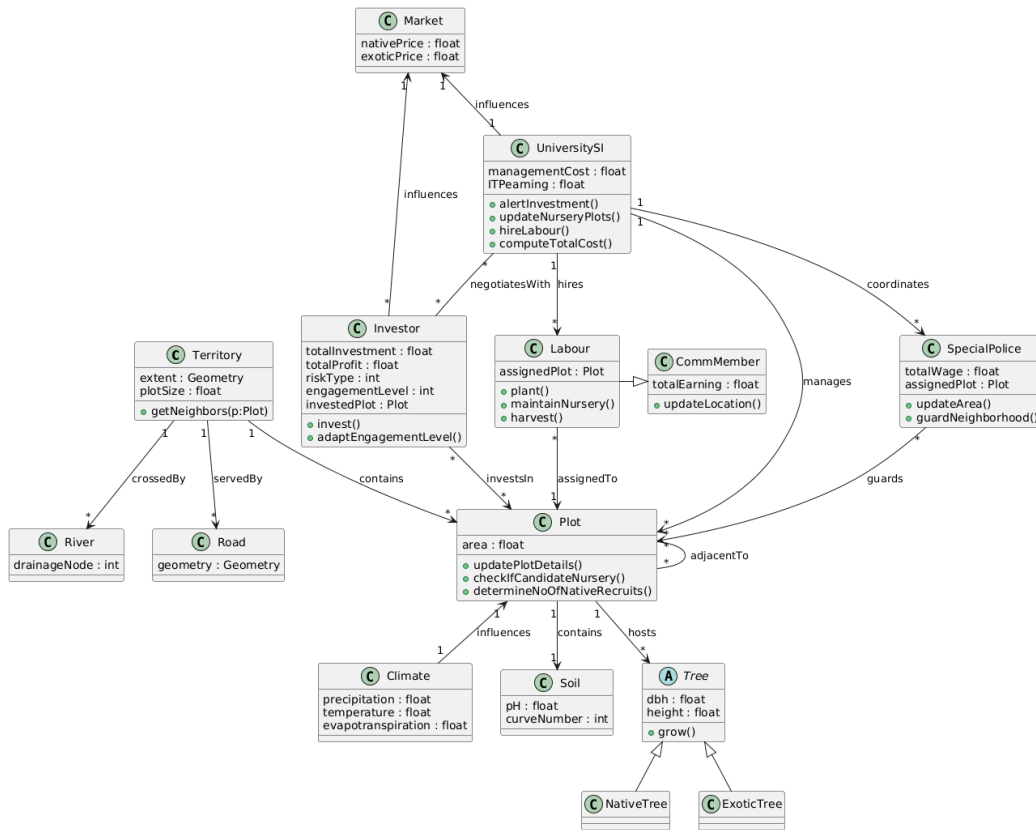


Figure 4.5: UML class diagram of the LUNTIAN model.

The biophysical entities, i.e., river, road, climate, and soil agents, define the environmental landscape and influence ecological processes such as tree growth, hydrology, and site productivity. The tree entities, central components of the model, are categorized into native and exotic types, where native trees generally follow growth dynamics characteristic of the Dipterocarpaceae family, while exotic trees are modeled after *S. macrophylla*. Trees are distributed across plots, each representing one hectare of land; plot attributes are shaped by interpolated soil and climate variables – including pH, rainfall, temperature, and evapotranspiration – as well as

proximity to roads and rivers.

The social entities are the human and institutional actors involved in plantation management. At the core is the university agent, representing the UPLB LGMO, which coordinates operations such as nursery supervision, labor deployment, planting, harvesting, salary disbursement, and financial monitoring. Nursery plots are managed by the university to produce seedlings for enrichment planting. The market agent supports economic dynamics by supplying external pricing information for timber and labor. While the university handles hiring directly, wages are benchmarked against market rates. Due to the absence of reliable time-series data in the Philippine context, both timber and labor prices are assumed to be constant throughout the simulation.

Other key social agents perform operational, economic, and enforcement roles within the ITP system. Investor agents finance plantation activities and exhibit different levels of risk tolerance (i.e., risk averse, risk neutral, or risk seeking), and their behavior adapts to investment outcomes, shifting between passive, active, or disengaged states. Labor agents, drawn from the local community or university, execute ground-level tasks such as planting, nursery maintenance, and harvesting, but under conditions of limited employment or low wages, some of them may transition into informal roles as independent harvesters; to mitigate such unauthorized activities, special police agents patrol designated zones and enforce institutional regulations. The broader community member agents represent the surrounding population and can dynamically switch roles – becoming formal workers, informal harvesters, or passive observers – depending on contextual factors such as employment availability and perceived benefits.

Process overview and Scheduling. The LUNTIAN model proceeds in monthly time steps. One complete simulation experiment executes a full harvest rotation – approximately 180 cycles, equivalent to 15 years for a 15-year harvest interval. Figure 4.6 presents an overview of the processes executed during each simulation cycle.

At initialization, the model instantiates the biophysical environment, representing the landscape as a grid of 1-hectare parcels, which serve as the fundamental spatial units in the model. Each parcel receives structural and environmental attributes – including soil properties and baseline climate conditions – based on forcing variables that give observed data values (time series) of the Climate agent. Using these inputs, the model calculates the initial amount of available water per parcel. As the simulation progresses, it updates temperature, precipitation, and available water monthly to reflect seasonal patterns.

Following environmental updates, the model sequentially executes five core sub-models that simulate the ecological, economic, and institutional dynamics of the ITP system. The stand growth submodel updates tree development through diameter growth, fruiting, recruitment, and mortality based on species-specific parameters and monthly climate data. Forest operations – including harvesting, en-

richment planting, and nursery management – are handled by the forest operation submodel, with activities restricted to investment-active plots, while nursery work occurs on selected parcels near mother trees. The investment process submodel identifies viable plots and simulates investor decisions according to risk preferences and projected returns. The employment dynamics submodel allocates labor from the university and nearby communities for plantation tasks and models informal harvesting behavior that may arise from unemployment or limited job access. Finally, the ITP policing submodel simulates enforcement through patrolling agents who monitor designated areas, detect unauthorized harvesting, and apply penalties using proximity-based rules. Together, these submodels enable the model to capture the system’s multi-dimensional interactions at a monthly scale.

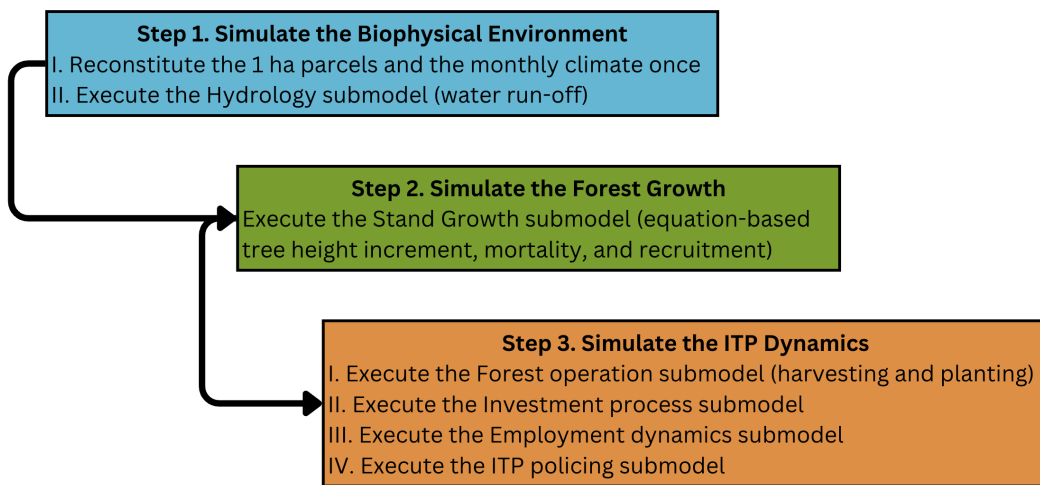


Figure 4.6: Scheduling of the monthly processes simulated by LUNTIAN

4.2.4.2 Design Concepts

The LUNTIAN model incorporates the design concepts outlined by [Grimm 2010], adapting them to the context of industrial tree plantation management. Beginning with *Basic Principles*, the model is grounded in the SES framework [Ostrom 2009] and integrates insights from resilience theory [Holling 1973], sustainability triad analysis [Purvis 2019], and economic decision theory [Gigerenzer 2011]. These principles are reflected at multiple levels: tree dynamics follow individual-based growth theory [Grimm 2005]; labor choices are informed by rational choice theory [Becker 1968] and informal economy research; and enforcement behavior draws on deterrence theory [Becker 1968], with spatial patrolling inspired by real-world law enforcement practices.

Emergence is considered in the design of the model, with outcomes such as unauthorized harvesting, investor disengagement, and labor market shifts arising from interactions between agents and their environment. Although individual behaviors (for example, investment withdrawal) are explicitly modeled, broader system pat-

terns arise through weak emergence [Bedau 1997]. Closely related is *Adaptation*, as agents adjust their actions in response to changing conditions. For example, investors may become passive under unfavorable risks, while community members alter their livelihood strategies when opportunities shift. These adjustments occur without formal *Learning* mechanisms: the model does not implement memory-based or reinforcement learning, but rather captures adaptive responses in simplified form.

The model also specifies explicit *Objectives* for each agent type: investors seek profit, community members pursue livelihood security, Special Police aim to deter unauthorized activity, and managers focus on sustainability goals. To act on these objectives, agents rely on *Sensing* locally available information, such as profitability signals, employment opportunities, or evidence of illegal activity. They also engage in *Prediction*, with investors estimating future plot profitability using risk-based expectations. Their *Interactions* are primarily indirect, mediated through labor contracts, harvesting dynamics, and enforcement responses, which collectively shape the broader behavior of the system.

Stochasticity is deliberately embedded in several processes, including profit outcomes, detection probabilities, and decision-making, to reflect the uncertainties inherent in forest governance. In contrast, *Collectives* are not modeled explicitly: agents act individually, and no group structures or collective decision-making bodies are represented. Finally, the design concept of *Observation* is implemented by systematically tracking indicators such as forest condition, employment levels, and harvesting activity. These outputs serve as the basis for analyzing system performance and interpreting emergent patterns.

4.2.4.3 Details.

Initialization. To create the biophysical aspect of the model, the climate, soil, road, river, plot, and tree entities are initialized at the start of the simulation. The values for climate, soil, and road are based on fixed baseline conditions: soil pH is not expected to change significantly over the 17-year rotation period; roads are treated as permanent infrastructure with fixed spatial locations; and forcing variables (e.g., precipitation, temperature, and evapotranspiration) are based on historical climatological averages rather than dynamic weather events, reflecting long-term environmental patterns rather than short-term variability. Dynamic climate projections were not included in this version to isolate social–ecological interactions without introducing additional uncertainty; future versions may incorporate climate change scenarios as data availability improves. The climate entities were initialized using raster files representing temperature, precipitation, and evapotranspiration values characteristic of the study region. Temperature and precipitation data were taken from 2010–2018 records provided by WorldClim, based on CRU-TS 4.06 [Harris 2020] and downscaled using WorldClim 2.1 [Fick 2017], while for evapotranspiration, the global map of monthly reference evapotranspiration at approximately 1 km resolution developed by [Zomer 2022] was used. The soil entity attributes, including pH values, were derived from maps provided by the Bureau of

Soils and Water Management [Bureau of Soils and Water Management 2023], while hydrologic soil group classifications were based on data from [Ross 2018]. Finally, the road and plot entities were constructed from vector files extracted from topographic and elevation raster data of the case study site provided by UPLB LGMO; these datasets are not publicly available.

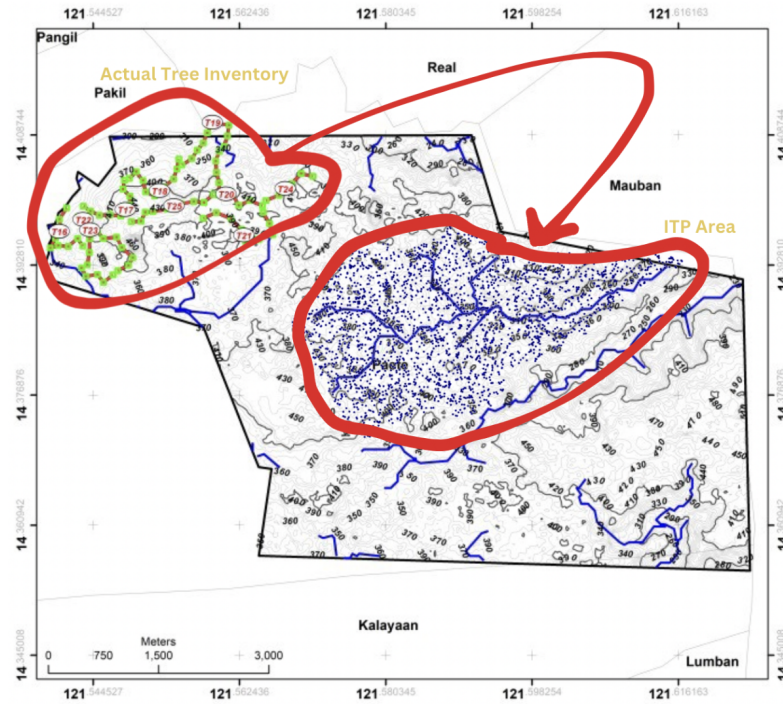


Figure 4.7: Location of the source data and the case study area within the LLG site. The section labeled “Actual Tree Inventory” indicates where the tree inventory was conducted, while the “ITP Area” denotes the region where the inventory data was applied.

Building on the initialization process, the tree entities were generated based on field inventory data and additional modeling assumptions. The individual attributes of the tree agents were derived from a 2019 tree inventory conducted in the northern part of the UP LLG site. In the absence of a dedicated inventory for the ITP section and due to the lack of publicly available, nationally aggregated data on tree densities in logged secondary forests in the Philippines, the initial population estimate was based on the modeling parameter used by Harja et al. (2023), whose work focused on simulating tree growth and carbon accumulation in the Philippine context using an assumed density of 400 trees per hectare. The original inventory contained 2,565 trees, and to approximate the density across the entire ITP area (1,411 hectares), this dataset was replicated 50 times, resulting in a total of approximately 128,250 trees – roughly one-quarter of the estimated tree density per hectare – and randomly positioned within the ITP area, as illustrated in Figure 4.7. This relatively low figure reflects the logged condition of the area and the presence of mixed land uses,

such as agroforestry, roads, and zones with intermittent human habitation.

Overall, the initial model environment consists of a landscape comprising 1369 parcels – excluding those intersected by rivers – each representing a 1-hectare plot of land (see Figure 4.8). Across this landscape, 127,652 tree stands are randomly distributed, with some parcels also containing roads designated for timber transport.

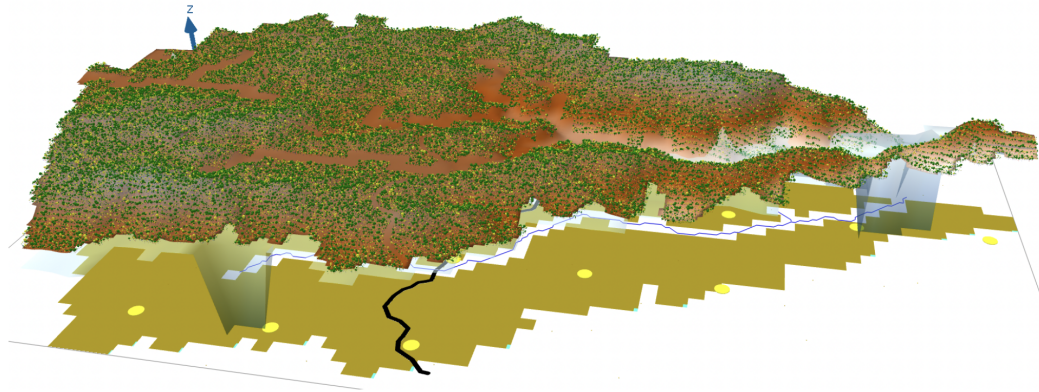


Figure 4.8: Initial environmental state of the simulation. Green dots denote native tree locations, and yellow dots denote exotic tree locations. Large yellow dots represent climate reference points (meteorological grid cells) used for spatial interpolation to estimate climate variables (e.g., temperature and precipitation) across the landscape.

The model also includes social agents: the market, labor agents, the university agent, investor agents, and special police agents. Each of them was assigned a random location outside the environment during initialization, and the number of labor, investor, and special police agents was determined by parameter values associated with each agent type. Table 4.1 lists the parameter variables along with their descriptions and their respective recommended value ranges.

Input Data. The model does not use input data to represent time-varying processes.

Submodels. To operationalize interactions within the ITP system, LUNTIAN integrates five interdependent submodels. Their design was informed by a combination of field observations, stakeholder input, and the relevant literature to ensure scientific validity and contextual relevance. Together, these simulate the ecological, operational, economic, labor, and governance processes introduced in Section 4.2.4.1 (Process Overview and Scheduling section). The following provides a detailed description of each submodel.

Stand Growth Submodel: It manages tree development by simulating the physical growth of tree agents, their fruit production, and mortality at each simulation step. This submodel is based on the framework for single-tree models proposed

Parameter	Description	Tested Values	Units
Nursery count	The number of nurseries that will be established.	{1, 3}	Number of nurseries
Community members	The total number of community members available for hire.	{15, 30, 50}	Number of individuals
Special police	The number of special police available in the ITP.	{1, 3, 10}	Number of individuals
Investor count	The total number of potential investors.	{5, 15, 50}	Number of individuals
Investor share on earning	The percentage of overall ITP earnings allocated to the investor once an investment deal has been made.	{0.3, 0.4}	Proportion (unitless %)
Investment rotation years	The total number of years until the plot invested upon is harvested.	{10, 15, 20}	Years
Timber price ¹ multiplier	The multiplier applied to the base harvesting timber price to determine the minimum price required for the ITP to be profitable.	{1.0, 2.0}	Unitless multiplier

Table 4.1: Model Parameters to be defined per simulation execution

¹ The default price-per-board-foot (where one board foot equals a volume of $12 \times 12 \times 1$ inches of wood) for harvested roundwood was based on the average national retail price of lumber in 2016 [Forest Management Bureau 2024]. Applying a 7-year inflation rate of 1.0342 [The World Bank 2022], the default price-per-board-foot for native trees is set to PHP 49.35, while that for exotic trees is PHP 45.06.

by [Vanclay 1994]. The growth process involves three core components: (1) diameter increment using species-specific growth equations; (2) mortality prediction based on probabilistic assessments; and (3) recruitment, which captures processes of maturation, fruiting, and seedling survival. Tree life stages are defined by diameter at breast height (DBH), progressing from seedling to sapling, then pole, and finally adult. The equations used in this submodel were based on the established literature (see Appendix B) and thus had already been calibrated.

Forest Operation Submodel: It introduces human-driven activities such as harvesting, planting, and nursery management. The harvesting and planting routines are adapted from the GAMA Forest Model described in [Arnejo 2023],

incorporating techniques such as selective logging [Tomboc 1993] and enrichment planting [Pinto 2021], which are executed only in plots under active investment agreements. Harvesting takes place twice – at the beginning and end of the investment cycle – while enrichment planting is triggered when either basal area or tree density falls below a defined threshold. During harvests, the university agent consults the market agent to determine roundwood prices (in board feet), after which profits are computed and allocated between the university and investors based on a tunable profit-sharing ratio.

Nursery management is tightly integrated with planting and harvesting to support the sustainability of enrichment efforts. This process, led by nursery laborers, begins with collecting seedlings from the ITP area and cultivating them in designated nursery plots; once mature, saplings – prioritizing native species – are transferred to investment plots, and if the supply is insufficient, the university supplements it by purchasing additional seedlings to meet planting targets. This system ensures a steady pipeline of native tree species, reinforcing the plantation’s long-term regenerative capacity.

Although specific silvicultural treatments such as pruning, thinning, and fertilization are not modeled as discrete actions, they are implicitly accounted for through labor and maintenance costs (see Appendix B). These aggregated costs reflect typical plantation upkeep activities that enhance tree growth and productivity. However, the model considers only the revenues from final harvests when calculating economic returns, while intermediate income streams – such as those from pruned biomass – are excluded to maintain the focus on maximizing net returns from full harvest cycles.

Investment Process Submodel: It facilitates the evaluation and allocation of investment opportunities and is activated once a set number of nurseries are established to ensure that the ITP can adequately support incoming investment requests. Investable plots are then offered to potential investors categorized by risk preference: risk averse (investing with a 0.25 probability if projected gains are $< 50\%$), risk neutral (0.50 probability), and risk seeking (0.75 probability if gains are $\geq 50\%$), following [Abidin 2023]. These probabilities determine the likelihood of transitioning from an “interested-passive” state – where investors are aware but uncommitted – to an active investment state. After completing an investment, each investor evaluates the outcome; if the result is deemed unsatisfactory, the investor may transition into a “not-interested passive” state, where the probability of the investor remaining disengaged ($P(NI)$) or returning to the “interested-passive” state ($P(Interested)$) is governed by their risk profile. Figure 4.9 illustrates these state transitions.

The design of the investment process submodel was guided by stakeholder input from a meeting with the Land Grant Management Office (LGMO), which played a key role in shaping the intended role of investors in the planned ITP implementation. Based on this meeting, the ITP is conceptualized as a program to engage potential investors – particularly university alumni – by inviting them to finance one-hectare parcels, guiding the representation of investor agents as key initiators of plantation

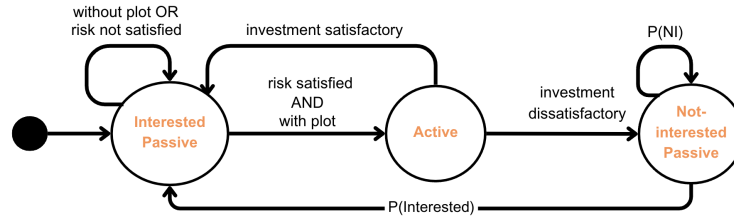


Figure 4.9: State-transition diagram for the investor agent.

activity.

Employment Dynamics Submodel: It governs the allocation of labor resources and captures transitions between formal employment and informal harvesting. This submodel operates in three phases, initial harvesting and planting, mid-cycle maintenance, and final harvesting and replanting. Community members and university workers form the labor pool.

To address labor shortfalls, the university issues open hiring calls whenever demand exceeds supply. Workers evaluate job opportunities by sensing the presence of other laborers and comparing expected wages with potential income from independent harvesting. If a community member remains unemployed for several months, they may eventually shift to informal harvesting – particularly in fringe parcels at the plantation’s border. This mechanism reflects field reports of labor competition observed at the study site and is contextualized by broader historical precedent. [Jurvélius 1997] documents how as early as the 1970s, an estimated 200,000 upland families across the country were already engaged in shifting cultivation; forestry experts at the time expressed concern that providing more efficient harvesting tools might unintentionally expand unauthorized timber extraction. These insights support the submodel’s assumption that labor scarcity can trigger transitions from formal employment to informal, unsanctioned forest use.

The employment dynamics submodel, therefore, captures the evolving tension between cooperative labor systems and opportunistic resource use. The full progression of laborer engagement is illustrated in Figure 4.10.

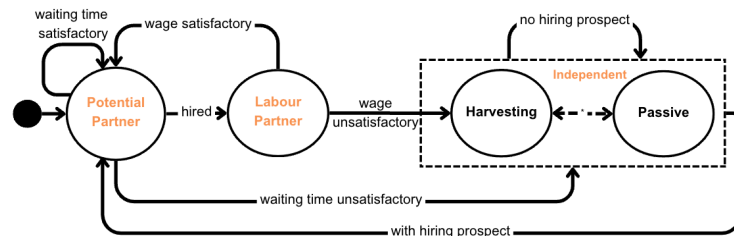


Figure 4.10: State-transition diagram for the laborer agent.

ITP Policing Submodel: It introduces a spatial enforcement mechanism to maintain order and discourage unauthorized activities – particularly illegal harvesting – within the plantation. Policing agents represent special police officers

who patrol the ITP area, with only laborers and these agents being permitted to enter the plantation in the model; while real-world access could include external actors, such complexity is beyond the current model’s scope. Patrols are repositioned every three months to simulate unpredictability, and enforcement occurs when a community member enters a police agent’s observable range, triggering a “catch” event. This results in the laborer forfeiting any financial gain, becoming inactive, and accumulating a violation count. These penalties are designed to reinforce rule compliance and deter repeated infractions.

The design of this submodel was informed by a site visit in January 2023, during which the researchers were escorted by special police assigned to monitor the site. Informal interviews conducted during the visit revealed that their duties included regular patrolling, discouraging unauthorized activities, and intercepting informal harvesters; the officers also shared that patrol teams operate in multiple groups and rotate locations periodically – patterns directly reflected in the modeled agent behaviors, including spatial movement and group deployment.

4.2.5 Model Assessment and Exploration

Due to limited assessment data, model validation was conducted solely on the biophysical layer. Simulation outputs from LUNTIAN were compared with those generated by 3PG2PY [Song 2022], an adaptation of the widely used 3PG forest growth model [Landsberg 1997], standardizing key input parameters across the models to enable direct comparison. The 3PG2PY was selected because its structural and functional configuration closely aligns with that of LUNTIAN: it relies on similar input variables (stand age, tree biomass, stand volume, soil water, and canopy cover), operates on a monthly time step, and requires primarily weather data; additionally, it has been successfully applied to long-term simulations spanning up to 120 years, producing ecologically realistic growth trajectories [Landsberg 1997]. The assessment focused on two core output variables: mean diameter at breast height (mean DBH, in cm) and stand basal area (SBA, in m^2). To account for differences in forest composition, the evaluation was performed separately for two scenarios – one involving only native species and another involving only exotic species – reflecting the original 3PG model’s design for monospecific plantations.

The assessment procedure comprised several key steps: First, the LUNTIAN experiment was run, during which the initial and final values of the observed variables – mean tree DBH and basal area per plot – were recorded. Next, 3PG2PY was executed under the same initial conditions, and the final values of the observed variables were also recorded. Finally, mean DBH and basal area per plot from both models were compared.

Two evaluation methods were employed to determine whether LUNTIAN accurately captures tree growth dynamics and reliably simulates forest stand development. The first method, Mean Absolute Percentage Error (MAPE) [Kim 2016], quantifies model alignment accuracy by calculating the average percentage deviation of forecast values, using the formula

$$\frac{1}{N} \sum_{t=1}^N \left| \frac{A_t - F_t}{A_t} \right|$$

where A_t represents the actual values generated by the 3PG2PY model (serving as the reference model) and F_t represents the forecast values produced by the LUNTIAN model at data point t , with N being the total number of data points. Good model alignment was interpreted using established thresholds: MAPE < 10% indicates highly accurate predictions, 11–20% reflects good accuracy, 21–50% is considered reasonable, and values exceeding 51% indicate poor accuracy [Lawrence 2009].

The second method, Fuzzy Kappa [McHugh 2012], compares observed and simulated maps using fuzzy logic to accommodate minor spatial discrepancies. The Fuzzy Kappa coefficient was calculated using the implementation available in the GAMA platform, which is based on the approach described in [van Vliet 2013]. According to [Landis 1977], the agreement levels on the interpretation scale for Kappa statistics are poor (<0.00), slight (0.00–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), and almost perfect (0.81–1.00). Because Fuzzy Kappa is designed for categorical or class-based raster data, the continuous model outputs (mean DBH and stand basal area) had to be discretized into bins before comparison.

This binning process groups continuous values into ranges, reducing sensitivity to small numerical differences and making spatial agreement more interpretable. To avoid arbitrary thresholds, multiple binning schemes were systematically tested, and the configuration that maximized the Fuzzy Kappa score for each variable was selected. In this way, the number of bins was not fixed in advance but determined by which scheme yielded the most meaningful structural agreement between simulated and reference maps, ensuring that the evaluation captured genuine similarities rather than minor numerical variation.

For model exploration, Sobol sensitivity analysis [Saltelli 2010] integrated into the GAMA platform [Taillandier 2019] was employed. Additionally, OpenMole [Reuillon 2010, Reuillon 2013], a comprehensive tool that offers a range of experimental methods was utilized to understand model behavior and capabilities. In particular, the Non-dominated Sorting Genetic Algorithm (NSGA2) was used for parameter optimization to answer the primary research question.

4.3 Results and Discussion

This section presents the key findings from the LUNTIAN model, organized into four main components: baseline forest dynamics, model alignment, sensitivity analysis, and simulation-based scenario exploration. The analysis begins with an examination of how the simulated forest evolves under purely ecological processes to establish a reference trajectory. This is followed by a model alignment phase that determines the model’s biophysical plausibility by comparing tree growth outputs with those generated by the widely used 3PG2PY model. A global sensitivity analy-

sis is then applied to identify the model parameters that exert the greatest influence on economic outcomes, particularly net earnings. Lastly, a series of simulation experiments – including critical parameter testing and multi-objective optimization – are conducted to identify configurations that promote ecological regeneration, economic viability, and social inclusion.

Together, these results support the model’s internal plausibility and its utility as a tool for simulation-based experimentation in sustainable industrial tree plantation strategies. While LUNTIAN has not yet been validated against real-world socio-economic outcomes due to limited field data, the model was designed primarily as an exploratory platform for understanding system behavior and trade-offs. Moreover, the model’s focus on institutional design and agent-based social dynamics is the reason climate change projections were not yet incorporated, as the primary objective was to explore the operational feasibility and stakeholder interactions against a fixed-climate baseline.

4.3.1 Baseline Forest Dynamics

To illustrate the model’s behavior, this section examines the simulated evolution of the forest landscape under baseline conditions. In this environment-only configuration, the LUNTIAN model simulates forest development driven solely by internal ecological processes – specifically, growth, fruiting, and mortality – without any external interventions such as harvesting or replanting. The simulation was initialized with 127,652 trees randomly distributed across the ITP area. As shown in Figure 4.11, the total tree population, primarily composed of saplings and seedlings, peaked at approximately 6 million in year 70.

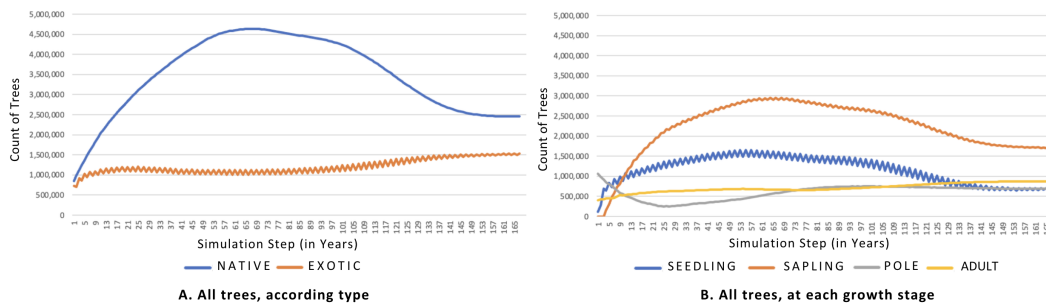


Figure 4.11: Tree growth trend over 2000 simulation cycles (approximately 165 years) in the absence of external influences. (A) Growth trend of trees categorized by species type – native versus exotic. (B) Growth trend of trees categorized by life stage – seedling, sapling, pole, and adult.

By year 145, the environment had stabilized with around 4 million trees, with a gradual shift toward older cohorts: the number of adult and pole-stage trees continued to rise, while younger populations held steady. These dynamics indicate that the forest had approached an ecological equilibrium by year 145, providing a structural reference point for evaluating model plausibility and informing subsequent

comparisons with models such as 3PG.

4.3.2 Model Alignment

The comparison with the 3PG2PY results revealed that LUNTIAN performed comparably in terms of mean DBH and SBA for both the native-only and exotic-only setups, for final stand ages of up to 80 years. As shown in Table 4.2, the error for both output variables is below 20%, meaning good alignment accuracy, establishing that LUNTIAN results are consistent with those of the 3PG2PY model. The Fuzzy Kappa analysis revealed varying levels of spatial agreement across forest types and variables. For native-only species, mean DBH yielded a value of 0.6047, falling just below the 0.61 threshold for substantial agreement and thus classified as moderate, while SBA was 0.7543, indicating substantial agreement. In exotic-only stands, both mean DBH (0.6612) and SBA (0.7680) showed substantial agreement, suggesting that the model performs slightly better in simulating the spatial structure of exotic species. The near-substantial mean DBH score for native species still reflects reasonably strong performance, though the broader use of growth equations based on the entire Dipterocarpaceae family – compared with the more uniform, mahogany-based approach for exotics – may have introduced additional variability and reduced precision for native stands.

	MAPE	Fuzzy Kappa
Native-Only		
Mean DBH	8.4914%	0.6047
SBA	10.5313%	0.7543
Exotic-Only		
Mean DBH	8.4148%	0.6612
SBA	14.4600%	0.7680

Table 4.2: Assessment Results. As reminder: (1) MAPE, the average percent deviation signifies high (< 10%), good (11–20%), reasonable (21–50%), and poor (> 51%) agreement; (2) Fuzzy Kappa, the agreement levels are poor (<0.00), slight (0.00–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), and almost perfect (0.81–1.00).

This performance gap reflects the broader variability in growth patterns among native species, which were modeled using generalized equations based on the Dipterocarpaceae family. These equations capture average trends but may not fully account for the species-specific traits, ecological niches, or competitive strategies of individual native taxa. In contrast, the exotic species – modeled solely on *Swietenia macrophylla* (mahogany) – benefited from more detailed, species-specific parameters derived from targeted empirical studies. The difference in parameter granularity led to more consistent outputs for exotics, while native species exhibited higher variance and reduced precision due to their ecological diversity and the reliance on aggregated growth assumptions. These findings indicate that even when accounting

for spatial distribution, the performance of LUNTIAN is comparable to that of the 3PG2PY model.

To assess spatial agreement, Figure 4.12 presents a set of spatial maps derived from both the LUNTIAN simulation and the 3PG2PY outputs. Specifically, the figure includes three types of maps for each variable: the simulated output from LUNTIAN, the reference from 3PG2PY, and a comparison map. Since Fuzzy Kappa is specifically designed for evaluating similarity between categorical or class-based raster data [Hagen-Zanker 2009], the continuous model outputs (specifically, mean DBH and stand basal area) was discretized into bins to ensure compatibility with the metric; this is a well-established preprocessing step in environmental modeling and is frequently employed to improve model interpretability and computational efficiency in approaches such as Bayesian Networks [Beuzen 2018]. To avoid arbitrary thresholds, multiple binning schemes was tested and selected the configurations that maximized Fuzzy Kappa scores for each variable; the resulting bin counts – 11 for native-only mean DBH, 15 for native-only SBA, 19 for exotic-only mean DBH, and 16 for exotic-only SBA – represent these optimized settings. This approach introduces a tolerance range that groups similar values, mitigating sensitivity to minor numerical variation and enabling more meaningful spatial comparisons.

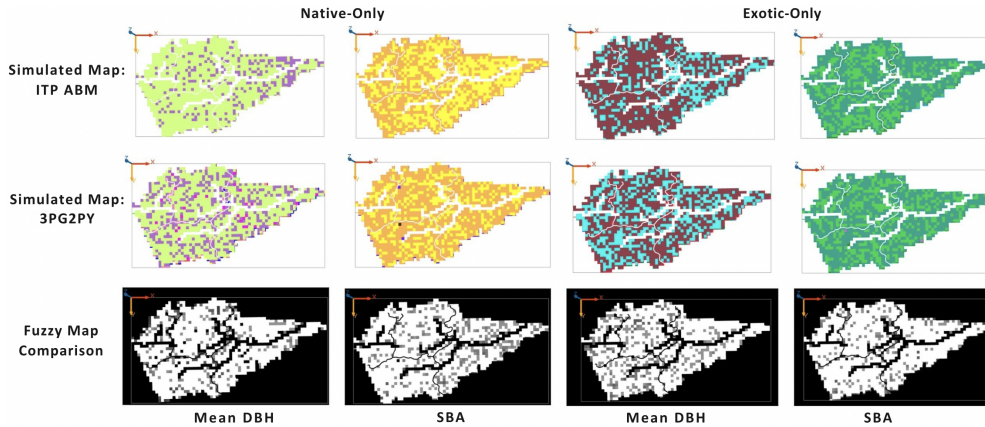


Figure 4.12: Fuzzy Kappa maps for LUNTIAN and 3PG2PY outputs. Each row shows the simulated output (top), the observed 3PG2PY output (middle), and the fuzzy comparison map (bottom). Only the fuzzy map comparison uses a consistent color scheme, where white indicates agreement between the LUNTIAN and 3PG2PY model outputs, gray represents disagreement beyond bin tolerance, and black denotes areas outside the modeled environment. The simulated and observed maps use automatically generated color gradients based on the distribution of each run and therefore do not include a fixed legend to avoid misinterpretation.

The fuzzy map comparison highlights areas of spatial agreement and disagreement between the simulated and observed outputs. Specifically, white areas correspond to matched values between the LUNTIAN and 3PG2PY maps, gray areas indicate mismatches beyond the defined bin tolerance, and black areas fall outside the plantation boundary and are excluded from the comparison. While these

maps suggest broad discrepancies and localized clustering – particularly near river networks – such patterns remain speculative. Further quantitative analysis and statistical validation are required to confirm the significance of these spatial structures and understand their ecological or model-driven origins.

4.3.3 Sensitivity Analysis

For the sensitivity analysis, overall final net earnings were used as the primary performance metric. While the broader evaluation of the LUNTIAN model considers ecological, social, and economic dimensions, this section focuses on evaluating the model’s robustness in representing long-term economic viability, which constitutes the principal research objective of the study. Final net earnings serve as a comprehensive economic indicator, reflecting the cumulative impacts of management decisions over time and providing a practical, interpretable basis for assessing sensitivity to key input parameters. Although LUNTIAN tracks multiple outcomes, including ecological regeneration and social labor transitions, the sensitivity analysis emphasized final net earnings because this metric best captures the long-term economic viability of the ITP. Social and environmental metrics were incorporated in the optimization phase (Section 4.3.4), where trade-offs among the three sustainability pillars were examined in greater depth.

Saltelli’s variance-based sensitivity analysis was applied to quantify the influence of model parameters on output variability [Saltelli 2008]. Specifically, both first-order and total-order sensitivity indices were computed for the following parameters: community members, nurseries, investors, special police officers, the share of investors in ITP earnings, and the length of one complete harvest rotation (see Figure 4.13).

In Sobol sensitivity analysis, the first-order indices are calculated by varying all parameters simultaneously, then mathematically isolating the contribution of each parameter via an integral over the input space. In contrast, the total-order sensitivity index accounts for the parameter’s overall contribution, including both its direct impact and all interactive effects with other parameters [Saltelli 2010]. This distinction is especially relevant in a complex agent-based system such as LUNTIAN, where socio-economic and ecological processes are tightly coupled. Parameters often do not act independently; their effects emerge through feedback loops and interdependencies. Thus, a high total-order index relative to the first-order index suggests that a parameter plays a crucial role in shaping system behavior through interactions with others – an important consideration in understanding the emergent dynamics of social–ecological systems.

For each parameter set, a full simulation of the ITP was executed – from initialization to the completion of the harvest rotation for every active investor – and Sobol analysis was performed using 420 Saltelli samples.

Based on the Sobol sensitivity analysis results, the investor count clearly exerted the strongest influence on the final net earnings, as shown by its high total-order index and the notable gap between its first-order and total-order values. This

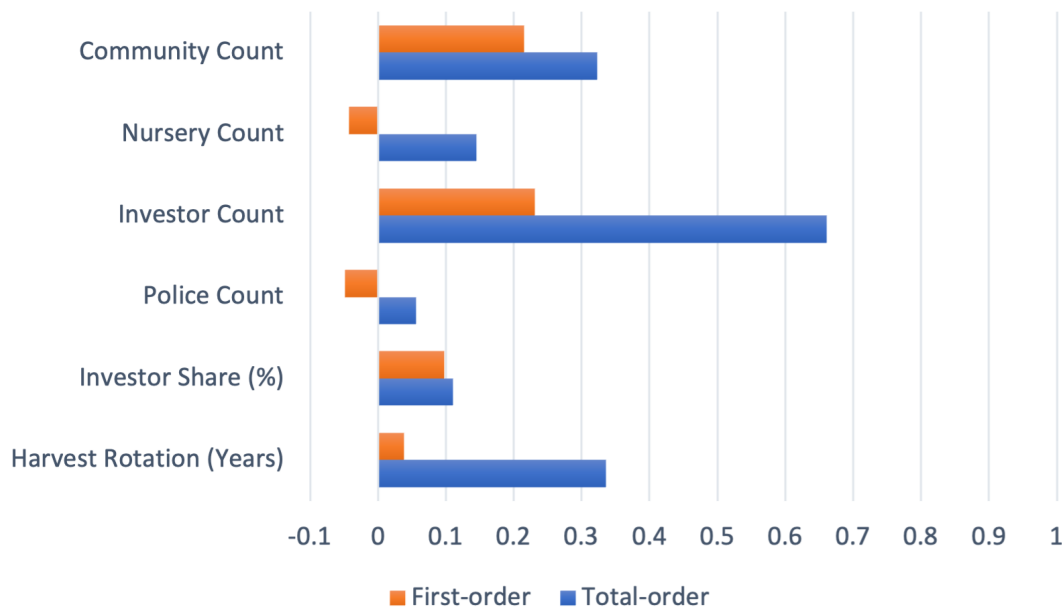


Figure 4.13: Sensitivity analysis of variables affecting final net earnings.

indicates that the investor count not only had a substantial direct effect but also interacted meaningfully with other parameters. Higher investor numbers generally lead to more financed plots and increased labor demand, which boosts earnings; however, this relationship is not linear – saturation effects, coordination challenges, and management overhead may reduce marginal gains as investor numbers grow.

Harvest rotation also exhibited a significant influence, with its total-order index exceeding the first-order value, suggesting strong interactive effects. Shorter rotations may increase cash flow and accelerate returns, but they typically reduce final biomass and potential yield; conversely, longer rotations can enhance ecological regeneration and total harvest volume, but they accumulate higher costs and delay revenue realization. This underscores the importance of identifying an optimal rotation period that balances short-term returns with long-term sustainability.

The community count and investor share also showed moderate-to-high influence on earnings. The former's slightly higher indices reflect its impact on labor availability and associated costs, while investor share directly shapes the distribution of profits. In contrast, the police count and nursery count had relatively lower but still measurable effects, indicating that while important for governance and regeneration, their roles are less dominant in driving overall profitability.

Overall, these results highlight how LUNTIAN's performance is shaped by the interplay of economic, ecological, and social levers and demonstrate the need for careful calibration to achieve balanced, sustainable outcomes.

Slightly negative first-order indices was also observed on the variables nursery count and police count. In theory, Sobol indices are expected to lie between 0 and 1 because they represent the proportion of output variance attributable to each input parameter. However, negative values can occur, particularly when the true

sensitivity of a parameter is near zero. This phenomenon is primarily attributed to numerical inaccuracies in the estimation process. For example, the Saltelli method may yield slightly negative values for factors with negligible influence due to errors in covariance estimation – a problem that is exacerbated in stochastic simulations such as those generated with ABMs [Saltelli 2008]. Moreover, when these methods are applied to ABMs, independent sampling and the high dimensionality of the parameter space further degrade the accuracy of the estimates, resulting in negative sensitivity values. Although some researchers set these negative values to zero for interpretability, doing so may introduce bias into the analysis [Thiele 2014, ten Broeke 2016]. Given that the first-order indices for these parameters remain within -0.05 , it can be concluded that neither variable significantly contributes to the variance in the evaluation metric, namely, the final net earnings.

4.3.4 Simulation-based Scenario Exploration

The primary research question driving this modeling effort is the following: “*Can the ITP be implemented sustainably, and if so, what are the optimal parameters to maximize returns?*” To address this, an optimization analysis was conducted to identify configurations that satisfy three key sustainability criteria – environmental, economic, and social – based on the sustainability triangle framework introduced by Campbell (2003) [Campbell 2003]. Environmental sustainability was evaluated by measuring the final tree population at the end of each simulation, economic sustainability by calculating investors’ and net profit, and social sustainability by examining the number of community members transitioning to independent harvesting. Therefore, in our analysis, the optimal configuration is defined as one that maximizes the tree population (ecologically sustainable), generates a positive net profit for both the university and investors (economically sustainable), and minimizes the number of community members engaging in independent harvesting (socially sustainable).

The following simulation scenarios were investigated to determine the model’s behavior under varying conditions:

- Critical parameters: Intended to observe the impact of key variables identified during the sensitivity analysis.
- Main scenario: Focused on exploring the interplay among environmental, economic, and social factors to achieve sustainable outcomes.

4.3.4.1 Critical parameters

Experiment Design. To assess which parameters most significantly influence the profitability of the ITP, a targeted analysis was conducted on four variables identified in the sensitivity analysis: (1) number of community members, (2) investor count, (3) investor profit share, and (4) harvest rotation years. Each parameter was varied individually while holding the others constant at their maximum tested

values. This method allowed us to isolate and evaluate the effect of each parameter on the model's primary economic output-net earnings.

Five simulation experiments were explored:

- All Max: All critical parameters set to their maximum values.
- Rotation Min: Harvest rotation years set to the minimum.
- Investor Share Min: Investor profit share set to the minimum.
- Investor Count Min: Investor count set to the minimum.
- Community Members Min: Number of community laborers set to the minimum.

Results and Analysis. Figure 4.14 summarizes the net earnings across the five simulation setups. In four scenarios – All Max, Rotation Min, Investor Count Min, and Community Members Min – the model produced negative net earnings, underscoring how small variations in key parameters can push the ITP into unprofitability. Only the Investor Share Min scenario resulted in positive earnings, indicating that reducing the investor's profit share can effectively absorb high management costs.

These outcomes are consistent with the sensitivity analysis (Figure 4.13). The investor share parameter showed a strong direct influence on net earnings, as indicated by similar first- and total-order Sobol indices; in contrast, other parameters had greater interaction effects, contributing to output variability mainly through their interplay. This non-additive behavior highlights the importance of managing parameters in combination rather than isolation.

4.3.4.2 Main scenario

Experiment Design. An optimization experiment was conducted by using the NSGA2 algorithm implemented in OpenMole [Reuillon 2013]. The goal was to identify a parameter configuration that satisfies environmental, economic, and social sustainability criteria. All the parameters specified in Table 4.1 were used at their tested values. The outputs optimized included the following:

- Environmental sustainability: Maximize final tree population.
- Economic sustainability: Maximize net earnings and investor profit.
- Social sustainability: Minimize number of community members engaging in independent (unauthorized) harvesting.

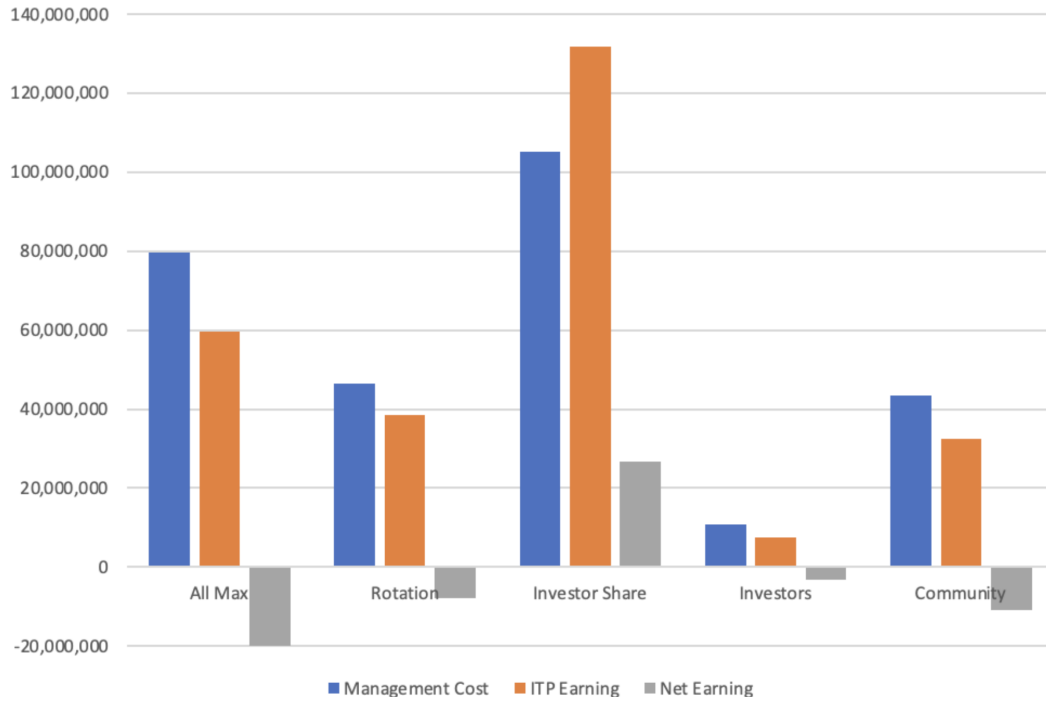


Figure 4.14: Comparison of management cost, ITP earnings, and net earnings across five parameter configurations: All Max, Rotation Min, Investor Share Min, Investor Count Min, and Community Members Min.

Results and Analysis. During the NSGA2 optimization (run over 100 evolutions), all simulation outputs were logged across the explored parameter space. These logged results were then used to generate the pairwise correlation matrix shown in Figure 4.15. The matrix captures relationships between key output variables based on the full set of simulations produced during the optimization process. For instance, a strong positive correlation (0.617) was observed between tree population and management costs. This indicates that simulations with higher tree populations also tended to report higher management costs – primarily due to the increased labor and nursery demands associated with maintaining and enriching denser tree populations.

Similarly, investor profits were positively correlated with both management costs and tree population, suggesting that scenarios promoting forest growth also support economic returns, albeit with higher operational expenses. A strong negative correlation was observed between tree population and net earnings, indicating that scenarios promoting forest growth tended to incur higher labor and nursery maintenance costs, which in turn reduced net profitability – especially when not offset by proportional revenue increases.

A strong correlation can also be noticed between partner profits from community-hired laborers and independent profits from unauthorized harvesters. This likely indicates that in scenarios with more labor opportunities and higher

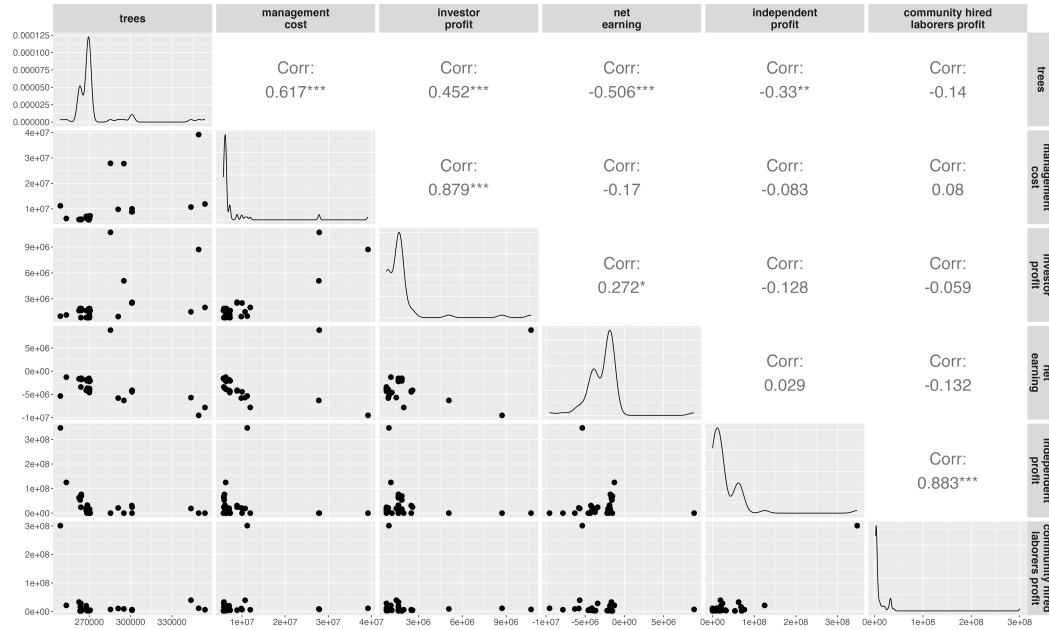


Figure 4.15: Pairwise correlation matrix of observed variables. Asterisks indicate the strength of correlation: * for values ≥ 0.2 , ** for values ≥ 0.3 , and *** for values ≥ 0.4 .

wages, independent harvesting may still occur – likely because not all community members are hired, as the number of available workers exceeds labor demand.

Final Configuration and Outputs. The best-performing parameter combination obtained with the optimization process is nursery count = 3, price multiplier = 2, investor earning share (%) = 0.3, investment rotation years = 17, investor count = 50, police count = 3, and member count = 28. The outputs obtained under this configuration given a single optimized simulation are shown below (Table 4.3).

Output Metric	Value
trees	285,376
management_cost	PHP 27,923,416
investors_profit	PHP 10,699,486
net_earning	PHP 8,884,374
independent_profit	0
partners_profit	PHP 7,344,327

Table 4.3: Output metrics under the optimal configuration.

The optimal configuration identified by the LUNTIAN model demonstrates that sustainable ITP management is achievable through the strategic calibration of key parameters. A 55% increase in tree population over a 17-year harvest cycle – despite ongoing extraction – shows that forest regeneration can occur alongside commercial

harvesting when supported by appropriate management practices and investment timing. This finding challenges the assumption that profitability and ecological resilience are inherently at odds, offering a data-driven case for integrating long-term ecological goals into plantation planning.

Economically, the configuration produced strong net earnings for both the university and investors, even with a relatively modest investor share of 30%. The 30% investor share identified in the optimal scenario demonstrates that a modest yet meaningful return is sufficient to sustain investor interest while enabling the university to cover management costs and provide stable employment for community members. In the final optimized configuration, this arrangement – combined with a 17-year harvest rotation, 3 nurseries, 50 investors, 28 community laborers, and moderate enforcement (3 special police officers) – resulted in a 55% increase in tree population, PHP 8.8 million in net earnings, and 0 instances of unauthorized harvesting. These outcomes indicate that when key parameters are carefully calibrated, it is possible to concurrently achieve ecological regeneration, financial sustainability, and social harmony.

From a practical standpoint, this configuration reflects the real-world feasibility of designing ITP systems that attract investment without over-reliance on high investor returns. A 30% share proves adequate not only to yield PHP 10.7 million in investor profit but also to preserve forest cover and fund essential community labor, where community members would earn over PHP 7.3 million in wages. The absence of informal harvesting further signals a healthy labor management dynamic, where equitable job access and fair compensation reduce incentives for unauthorized forest use.

In the context of the SES framework, these results affirm that the model supports positive outcomes across all three core metrics: ecological (increased forest cover), economic (viable net income and investor return), and social (harmonious labor relations and inclusive benefit sharing). LUNTIAN thus offers a practical decision-support tool for stakeholders aiming to balance long-term ecological goals with inclusive economic development.

4.4 Conclusion

This chapter presented an agent-based model simulating an ITP operation within a mountain forest managed by the University of the Philippines Los Baños – Land Grant Management Office. The model integrates key biophysical processes with socio-economic dynamics, including investment decision-making, labor engagement, and forest policing. Simulation results indicate that the ITP can be managed to ensure environmental, economic, and social sustainability. Notably, despite ongoing harvesting activities over a 17-year rotation, the LUNTIAN model projected a 55% increase in final tree population relative to initial levels. This finding suggests that carefully calibrated management practices can support forest regeneration even under commercial harvesting regimes.

The model's biophysical outputs were aligned against the established 3PG forest growth model, with comparisons based on mean diameter at breast height and stand basal area showing acceptable error margins. Fuzzy Kappa coefficients also demonstrated substantial spatial agreement, and a sensitivity analysis identified key parameters – particularly investor earnings share and community member count – as strong drivers of management costs and net earnings. These results highlight how financial sustainability depends not only on ecological performance but also on the careful management of investment and labor dynamics.

Nonetheless, several limitations must be acknowledged. The behavioral rules governing social agents, including investors and laborers, are based on simplified heuristics rather than empirical calibration or adaptive learning. While informed by the literature and stakeholder input, these assumptions may not fully capture the nuances of real-world decision making, especially under uncertainty. Additionally, the model treats market variables – such as timber and labor prices – as static, thereby excluding the potential effects of economic volatility on system dynamics. Although the ecological processes were validated, the socio-economic parameters lack similar empirical grounding. Furthermore, the model is geographically specific to the UP LLG and may require significant adaptation to be transferable to other ITP contexts with differing environmental, institutional, or socio-political conditions.

Environmental dynamics are also simplified, with climate inputs being based on historical averages rather than incorporating projections of climate change or extreme events. Institutional complexity is partially modeled through special police enforcement, but broader policy and governance factors – such as land tenure reform, incentive schemes, or regulatory changes – are not yet integrated. These limitations point to several promising directions for future development, particularly in enhancing the model's realism and decision-support capabilities. Key priorities include integrating climate-change projections, simulating dynamic timber and labor markets, and incorporating adaptive learning mechanisms to better reflect how agents respond to uncertainty over time. Future work will specifically focus on using time-varying climate data to evaluate long-term system resilience, implementing learning algorithms that allow key social agents – such as laborers and investors – to adapt their behavior based on experience, and refining decision-making rules through improved empirical calibration. Together, these enhancements aim to capture more realistic socio-environmental dynamics and reinforce LUNTIAN's utility as a tool for exploring sustainable management strategies.

As with any simulation, simplification introduces the risk of omitting critical dynamics. However, models are inherently simplifications built with a specific purpose – not to capture every detail but to illuminate key interactions and trade-offs. LUNTIAN was intentionally designed as a scenario-exploration platform, aiming to capture essential system behaviors while maintaining interpretability, and its structure prioritizes the representation of core social-ecological processes relevant to industrial tree plantations. Future work may expand this foundation to include currently excluded variables, such as market volatility and broader institutional

complexity.

While this study does not propose direct prescriptions for ITP implementation, the simulation results offer meaningful insights into the conditions under which plantations could achieve ecological, economic, and social sustainability. The optimal configuration identified by the model reflects a balance of parameters – such as rotation length, investor share, nursery count, and labor availability – that produced positive financial returns, increased forest cover, and eliminated unauthorized harvesting. Rather than presenting a fixed blueprint, the model provides a flexible, evidence-based platform for exploring plausible management strategies and trade-offs. As such, LUNTIAN is best viewed as a tool for scenario exploration, communication, and in vitro experimentation – supporting stakeholders in identifying potential pathways, testing assumptions, and engaging in more informed discussions around sustainable plantation development.

Supporting Post-development Communication of Agent-based models: Application of ABM-VISTA to LUNTIAN model

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Chapter 5 represents a pivotal point in the dissertation, where the ABM-VISTA framework (Chapter 3) and the LUNTIAN model (Chapter 4) are brought together in practice. The integration of these two strands directly addresses the gap identified in Chapter 2, namely the persistent challenge of communicating agent-based models in the post-development phase, by operationalizing the conceptual and methodological foundations established earlier and testing their utility within a concrete socio-ecological case study.

5.1 Introduction

The integration of post-development communication frameworks with concrete agent-based models provides a critical test of whether innovations in transparency and accessibility can meaningfully change how models are interpreted and used. While frameworks such as ABM-VISTA are designed to transform simulation traces into visual and narrative forms, their value cannot be assessed in abstraction. Only when embedded in a substantive model do the strengths and limitations of such tools become apparent [Arnejo 2025a].

Applied to the LUNTIAN model of forest-based socio-ecological dynamics, ABM-VISTA generates communicative artifacts – process maps, workflow diagrams, and machine-generated narratives – that expose aspects of model behavior rarely conveyed in static documentation. Existing protocols such as Overview, Design concepts, and Details (ODD) and TRACE remain essential for reproducibility and structural transparency [Grimm 2006, Grimm 2014], yet they are limited in their ability to represent emergent dynamics, feedbacks, and executional contingencies [Manson 2020, Ekström 2024]. The integration of ABM-VISTA with LUNTIAN directly addresses this gap by grounding communication in execution traces, thereby highlighting agent interactions, decision pathways, and system-level patterns as they unfold.

By situating ABM-VISTA within an empirically grounded model, this chapter examines not only the communicative power of automated outputs but also the tensions they introduce. Different representational forms – maps, diagrams, narratives – privilege particular aspects of model behavior, raising questions about what is revealed, what remains hidden, and how these outputs might complement rather than supplant established practices. In this way, the integration of ABM-VISTA with LUNTIAN contributes an empirical basis for assessing post-development communication as a practical extension of socio-ecological modeling.

This chapter builds on these converging strands by embedding ABM-VISTA within the LUNTIAN model. By combining process mining techniques, workflow visualizations, and automated narratives, the integration tests whether methods originally developed in computer science and computational linguistics can concretely enhance the communicability of an applied socio-ecological model. In doing so, it responds to persistent calls for tools that reduce the opacity of ABMs and facilitate model accessibility for stakeholders especially in contexts where decisions are influenced by their understanding of complex system behavior [Kraan 2019, Ravaioli 2023, Arnejo 2025a].

5.2 Methodology and Implementation

The integration of the ABM-VISTA framework into the LUNTIAN agent-based model followed a structured workflow built around the framework’s core components: simulation logging, process visualization, and narrative generation. Figure 5.1 provides an overview of this integration, illustrating how the ABM-VISTA

pipeline was applied to extract, structure, and communicate the complex interactions and algorithmic logic embedded within the submodels of LUNTIAN.

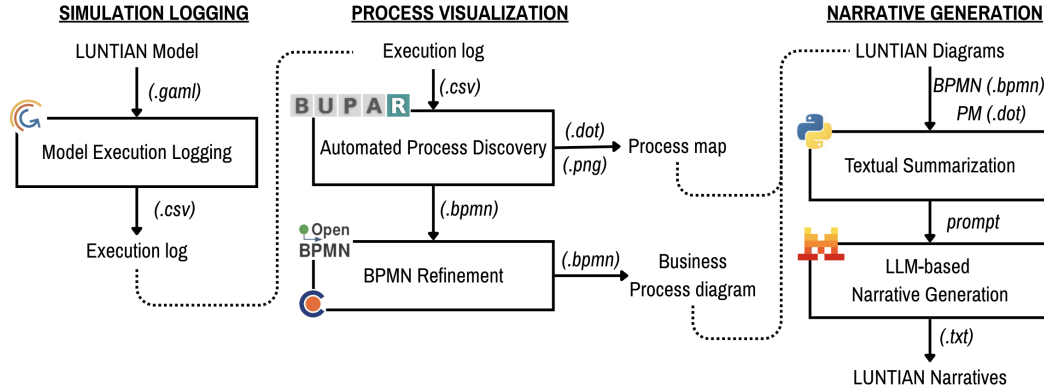


Figure 5.1: Schematic representation of how the ABM-VISTA framework was integrated with the LUNTIAN model

The LUNTIAN model was executed over a full harvest rotation using the following configuration: one nursery, 15 community members, one special police officer, 20 investors, and a 15-year harvesting cycle for invested plots. The simulation ran for 187 cycles, capturing the full progression of investment and harvesting activities across all managed plots. Events and actions were recorded into a single structured log file. In this log, method-related entries are associated with a nil resource, while variable-related entries assign nil to the activity field. A snippet of the resulting log file at cycle 50 is shown in Figure 5.2.

case_id	activity	time_stamp	value	resource
50	nil	01/01/1970 01:00	1466	[Variable]peers.trees
50	[action]neighborhoodInteraction.trees	01/01/1970 01:00	nil	nil
50	[action]calculateHeight.trees	01/01/1970 01:00	nil	nil
50	[action]setState.trees	01/01/1970 01:00	nil	nil
50	[action]treeGrowthIncrement.trees	01/01/1970 01:00	nil	nil
50	[action]stepAge.trees	01/01/1970 01:00	nil	nil
50	[behavior]growthModel.trees	01/01/1970 01:00	nil	nil
50	[action]checkMortality.trees	01/01/1970 01:00	nil	nil
50	nil	01/01/1970 01:00	11	[Variable]has_fruit_growing.trees

Figure 5.2: Snippet of the log file obtained at cycle 50

Following the generation of the simulation log, the ABM-VISTA framework proceeded through its remaining stages to generate three key artifacts designed to enhance the model’s transparency and interpretability – particularly in the context of stakeholder engagement. These outputs include: (1) a process map (PM), generated through process mining to reveal event sequences and behavior patterns; (2) a business process diagram (BPD), which visually organizes these patterns into structured agent workflows; and (3) a series of simulation narratives, produced using LLMs to communicate the model’s structure, dynamics, and emergent behaviors in natural language.

Each artifact type offers distinct strengths and limitations. Process Maps highlight temporal execution flows and allow users to trace how actions unfold during

simulation, though they can become visually dense in complex scenarios. Business Process Diagrams provide structured clarity and emphasize inter-agent coordination, yet they require selective abstraction that omits some details. Narratives are highly accessible to non-specialists, making them valuable for broad communication, but they may oversimplify or miss technical nuances. In this chapter, we focus primarily on PMs of agent actions rather than variable updates: while variable-level traces are essential for computation, they tend to generate extensive low-level detail that is less informative for stakeholders, as they rarely expose decision pathways or emergent patterns.

Taken together, these artifacts provide complementary views of the system, supporting deeper understanding and more accessible communication of the model across diverse stakeholder audiences. The following subsections present each artifact in detail.

5.2.1 Process Map

The first artifact generated by the ABM-VISTA framework are PMs that capture the temporal sequence of agent behaviors during simulation. Applied to the LUN-TIAN model – which includes ten agent types: university, trees, plot, road, soil, special police, market, labor, investor, and community member – Figure 5.3 provides an integrated view of how these agents interact, showing the ordered execution of their functions over the course of a simulation run.

As shown in Figure 5.3, the simulation begins with the `university_si_model` agent (Box 1), followed by the initialization of the environment, which includes the soil, plot, road, and tree agents (Box 2). The social agents are then introduced, starting with the university agent (Box 3). The cycle concludes with either the investor agent (Box 4), who finalizes investment decisions, or the environment agent (also in Box 1), which records the final simulation data.

To provide a more fine-grained perspective, individual PMs were also generated for each agent type. These highlight the specific sequence of functions performed and the interactions they entail. Figure 5.4, for example, presents the PM of the Community Member agent. The complete set of PMs for all agents is available in Appendix D.

In Figure 5.4, the activity ‘`behavior_updateLocation`’ serves as the central hub, reflecting frequent updates to the agent’s position within the environment. This activity typically leads to one of three outcomes – ‘`independent_harvesting`’, ‘`independent_passive`’, or ‘`potential_partner`’ – each ending the process. These correspond to three of the four possible behavioral states of a community member, the exception being ‘`labour_partner`’. The latter appears as an isolated activity without direct links to the main process flow, suggesting that once an agent becomes a university-hired laborer it follows a distinct behavioral pathway, separate from the typical sequence.

Figures 5.3 and 5.4 represent different forms of process models. Figure 5.3 is a Directly-Follows Graph-based process map, where rounded nodes denote aggregated

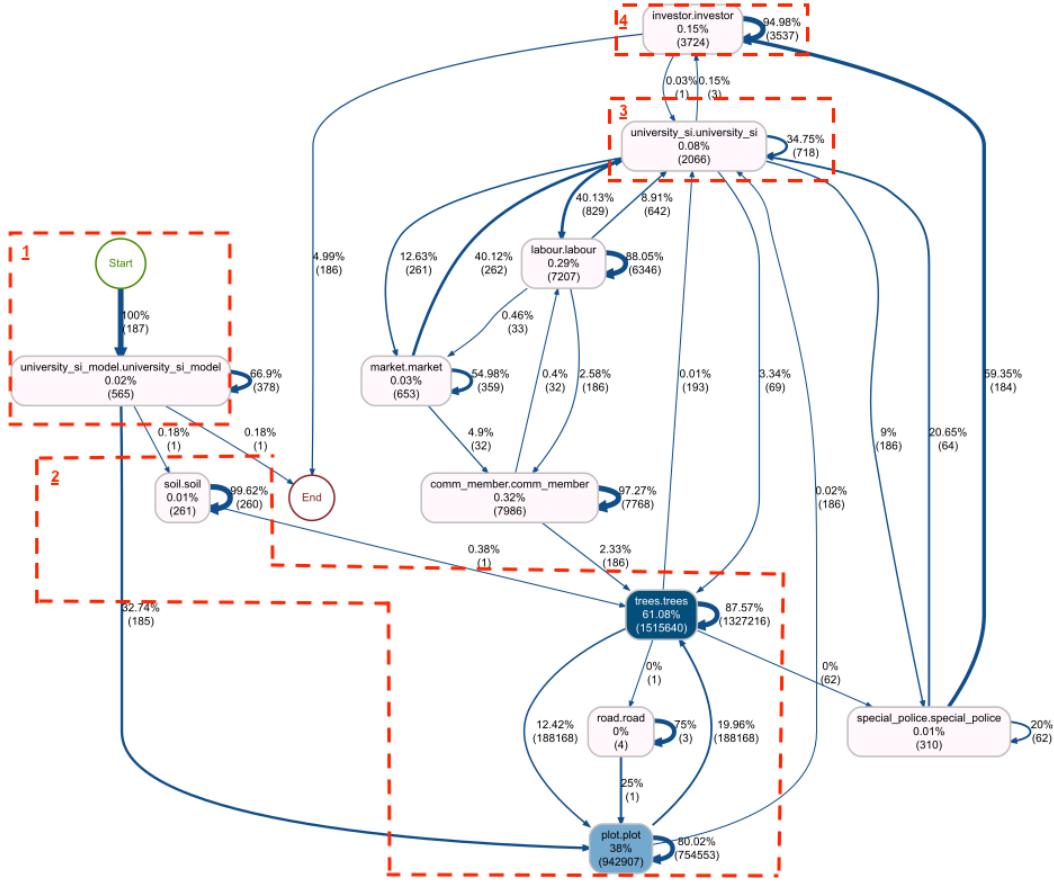
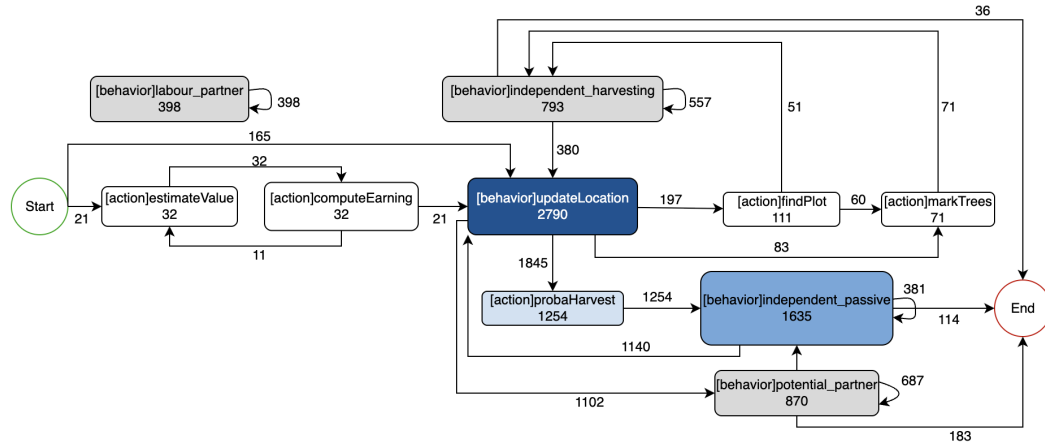


Figure 5.3: Agent interaction map showing the sequential execution of function calls across agent types in the LUNTIAN model. Node colors use the PuBu (purple-blue) scale to indicate frequency, based on values within the nodes. Edge thickness reflects corresponding weights along the edges.

event classes and edges indicate sequential relations. In contrast, Figure 5.4 depicts a causal network generated with the Inductive Miner algorithm, where squared nodes denote individual activities. These visual differences reflect the underlying algorithmic approaches, both of which are earlier presented in Section 3.3.3.

5.2.2 Business Process Diagram

The second artifact generated by the ABM-VISTA framework for the LUNTIAN model is a BPD which organizes behavioral sequences extracted from simulation logs into structured agent workflows. Using the Business Process Model and Notation (BPMN) standard, these diagrams depict the interactions between key agent types — such as investors, laborers, community members, special police, and plots — that are central to decision-making and socio-ecological outcomes. We focus on these agents to preserve clarity, since including all agent types would result in highly dense diagrams that obscure interpretive value, though the framework is capable



of producing full-system diagrams (see Appendix D). By separating activities into swimlanes and emphasizing inter-agent coordination, the BPD provides a clearer and more interpretable view of the system’s operational dynamics. Figure 5.5 illustrates the BPD of the special police agent as an illustrative example.

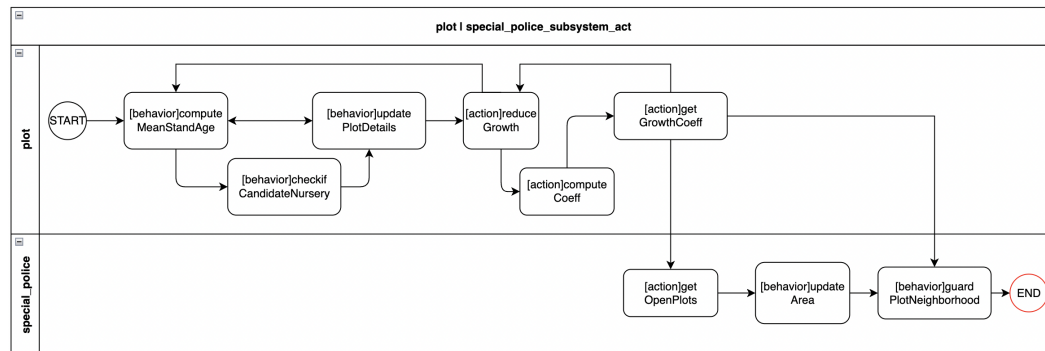


Figure 5.5 highlights the interaction between the special police agent and all the other agents (which is limited to plot agent in this case), illustrating how their functions are coordinated during simulation. The primary role of the special police agent is to guard a cluster of plots. According to the process diagram, the activities of the special police agent begin after the execution of the `getGrowthCoeff` method by the plot agent, which calculates the growth rate of trees based on current water content and expected precipitation. Appropriately, the special police agents are only activated once the plot's growth status has been fully determined, ensuring that guarding decisions are based on updated environmental data. The diagram further shows that if a police agent is already stationed at a plot, it proceeds to execute the `guardPlotNeighborhood` function. Conversely, plots not yet guarded are classified as `openPlots` and flagged as candidates for assignment to available

special police agents.

5.2.3 Model Narrative.

The third artifact produced by the ABM-VISTA framework for the LUNTIAN model is a model narrative, which synthesizes simulation log data into coherent, interpretable text that reveals the internal logic and behavioral dynamics of the model. Building on the principles and methods introduced in Chapter 3, this component utilizes LLMs to transform structured execution traces into stakeholder-accessible narratives. Rather than serving as simple descriptions, these narratives function as analytical tools that highlight agent behaviors, submodel mechanisms, and emergent system dynamics. The textual outputs are designed to bridge the gap between technical implementation and stakeholder understanding, enabling users to engage with the model’s key elements without requiring prior expertise in programming or simulation design.

For the LUNTIAN model, the generated narratives include a high-level overview that introduces the agent structure, environmental configuration, and temporal logic of the simulation. Additional narrative segments delve into specific submodels, highlighting how these processes unfold over time through agent interactions. Finally, synthesized insights drawn from the simulation outputs provide decision-relevant interpretations of emergent patterns, offering stakeholders a narrative pathway through the model’s complexity. A condensed version of these narratives is presented below, with the full texts available in Appendix E. This condensed form was also produced by the LLM as a complementary step, ensuring that the manuscript remains accessible without losing the connection to the full, automatically generated outputs.

Model Overview according to ABM-VISTA

LUNTIAN is a simulation model featuring a dynamic ecosystem of eleven interacting actors: market, special_police, comm_member, investor, plot, road, model, soil, trees, university, and labour. Each plays a specific role in shaping the system’s ecological and economic outcomes. The simulation begins with environmental setup by the ‘model’, triggering water flow and precipitation that affect tree growth. Trees undergo lifecycle processes – growth, mortality, and recruitment – driven by both environmental and internal factors, which in turn impact soil and plot conditions. ‘Labour’ is central, interacting with most actors to plant, harvest, manage nurseries, and maintain roads. Its decisions are influenced by economic assessments from the ‘market’, which evaluates profit, yield, and viability. ‘Special_police’ secure plots and influence ‘comm_members’, who mark and harvest trees independently. These community members operate based on probabilistic models, affecting tree populations and plot status. ‘Investors’ drive economic activity by identifying opportunities and notifying ‘university’, which coordinates planting, monitors saplings, and manages costs to balance growth and sustainability. Environmental feedback loops continue as

‘soil’ and ‘plot’ conditions evolve, influenced by trees and weather patterns. Roads facilitate labour and resource movement. The emergent system reflects a balance of ecological health and economic viability, showing how human decisions, environmental conditions, and institutional roles interact to shape sustainable forest management.

Submodels according to ABM-VISTA

The LUNTIAN model is composed of nine interconnected submodels, each capturing distinct but overlapping dimensions of the simulation. The Market Dynamics Submodel manages financial evaluations like calculating board feet and profit multipliers that guide economic decisions. The Economic and Labour Interactions Submodel centers on labor tasks such as planting and harvesting, linking them to investment and university activities. Environmental processes are simulated in the Environmental Management Submodel, which handles tree growth, soil health, and water dynamics. The Investor and Risk Management Submodel captures how investors make decisions based on risk levels and projected returns, influencing where and how resources are allocated. The Community and Harvesting Submodel involves community members in tree marking and plot management, bridging local participation with broader economic activities. The Plot and Growth Monitoring Submodel oversees the state and regeneration of specific forest plots. Security concerns are addressed by the Special Police and Security Submodel, which monitors unauthorized use and ensures compliance. Infrastructure dynamics, such as road maintenance and access, are handled in the Transportation Infrastructure Submodel. Finally, the Simulation Initiation and Termination Submodel manages the beginning and end of simulation runs, including environmental setup like precipitation and water flow. Together, these submodels create a multi-layered and holistic simulation of forest-based socio-economic-environmental interactions.

Key Insights according to ABM-VISTA

The LUNTIAN model offers a range of insights that can support decision-making in forest management, economic planning, and policy design. For forest managers, it illustrates the complexity of ecological and human interactions, showing how individual decisions ripple through the system and impact overall sustainability. It serves as an economic analysis tool by revealing how labor costs, market prices, and investment strategies shape profitability. Environmental insights include the role of road development and harvesting in altering ecosystem functions. Policymakers can use the model to simulate the effects of new regulations or land-use interventions. The model emphasizes that interactions between actors are highly interdependent, and outcomes are influenced by dynamic and probabilistic processes, mirroring real-world uncertainties. Environmental conditions such as soil and water availability are pivotal to tree growth and sustainability, while labor availability and effectiveness are central to operational success. The model also uncovers critical vulnerabilities – such as how tree mortality can abruptly halt investment and labor activities –

highlighting the need for integrated and adaptive forest management approaches.

5.3 Evaluation and Results

To assess the communicative utility of the ABM-VISTA framework, two forms of evaluation were conducted. First, a preliminary evaluation session was held in which visualizations derived from the LUNTIAN model were presented to forestry and computer science graduate students. This early assessment informed the development of ABM-VISTA by providing feedback on the usability of simulation-derived visualizations, particularly regarding the effort required and the clarity they offered in understanding the model. Second, a comparative analysis was conducted between traditional model documentation – specifically, the ODD protocol – and the narrative output of ABM-VISTA. This comparison aimed to evaluate the added value of dynamic, execution-based narratives in model communication.

5.3.1 Initial Student Evaluation

An initial presentation of the ABM-VISTA visualizations was conducted at the University of the Philippines Los Baños on April 8 and 12, 2024. Graduate students in computer science and forestry were invited, as they represent stakeholder groups likely to engage with ABMs for exploration, replication, and extension. During the session, participants explored the LUNTIAN model, ran a set of simulations, and afterward responded to evaluation questions assessing the clarity and usefulness of ABM-VISTA. The visual outputs consisted of both Process Maps (PMs) and Business Process Diagrams (BPDs), which at that stage represented the first version of the ABM-VISTA pipeline. The evaluation therefore captured student reactions to the pre-LLM iteration of the framework, providing feedback that later informed the integration of narrative generation. The full questionnaire used to evaluate stakeholder perceptions is presented in Table 5.1; the instrument was designed to assess usability, clarity, and the effectiveness of the generated outputs in supporting understanding of the LUNTIAN agent-based model. Respondents rated their agreement with each statement using a 5-point Likert scale ranging from “Strongly Disagree” to “Strongly Agree.” The evaluation was conducted in accordance with ethical research practices, including informed consent, voluntary participation, and anonymization of responses in line with institutional guidelines.

Nine students participated in the session (see Figure 5.6). Their responses to each question were averaged, with a maximum score of 5. Based on Figure 5.7, on average, participants found the visualizations easy to navigate and helpful in understanding the model. Many highlighted their usefulness in identifying frequently activated agent behaviors and key system variables. This ability to visually trace agent interactions during simulation was seen as a strength in making the model logic more accessible and interpretable.

The evaluation also revealed limitations. Some participants found the visualizations visually dense, particularly when presented with the full operational flow

Table 5.1: Evaluation Questions [1: Strong Disagree, 2: Disagree, 3: Neutral, 4: Agree, 5: Strong Agree]

Statement	1	2	3	4	5
1. I think I would like to use the visualizations when learning a new ABM					
2. I found the visualizations unnecessarily complicated					
3. I thought the visualizations was easy to understand.					
4. I think I would need the support of a technical person to link the simulation model with the visualizations					
5. I would imagine that most people interested in learning a new model would understand the visualizations very quickly					
6. I found the visualizations very cumbersome to understand					
7. I felt very confident when understanding how the simulation works with the help of the visualizations					
8. I needed to learn a lot of things before I could use the visualizations to understand an ABM					

of the simulation. Two participants indicated that they preferred starting with a simplified overview or summary of the model structure before engaging with the detailed diagrams. This feedback informed later iterations of ABM-VISTA, leading to the inclusion of both summary views and layered detail. In this way, the session not only tested usability but also provided formative input that shaped the tool's development to better support diverse user needs.



Figure 5.6: Testing and evaluation of the generated visualizations for LUNTIAN ABM with interested students

For clarity, Figure 5.7 summarizes responses to the eight Likert-scale questions listed in Table 5.1. Questions 2, 4, 6, and 8 were negatively worded to test response consistency (e.g., Q2: ‘I found the visualization unnecessarily complicated’). This design balanced positive and negative phrasing, ensuring a more reliable assessment of usability.

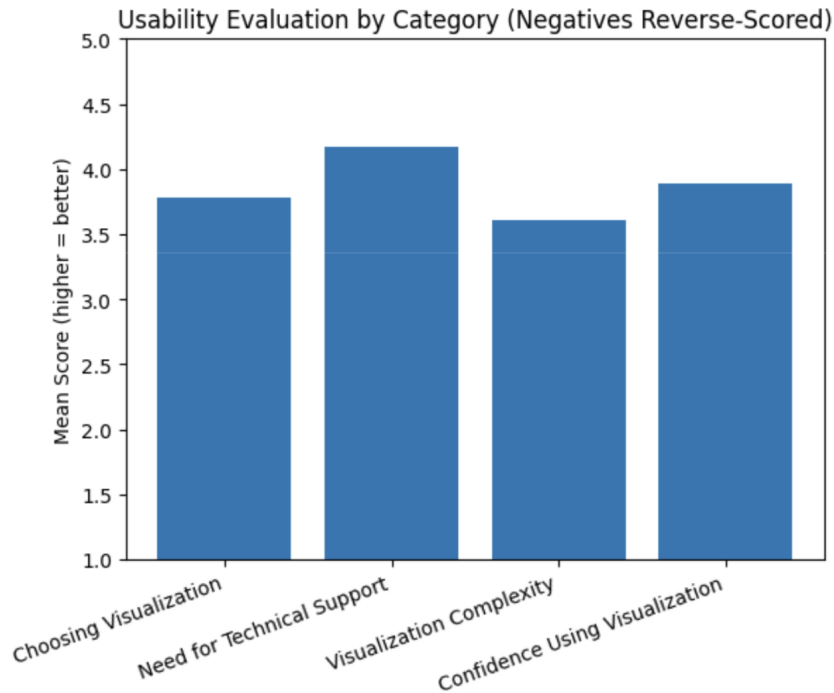


Figure 5.7: Results of the visualization usability evaluation. Negatively worded items were reverse-scored following standard procedures [DeVellis 2017], so that higher values indicate higher levels of each construct. Scores were then averaged within each of the four categories.

5.3.2 Comparative Analysis

The current implementation of ABM-VISTA, as applied to the LUNTIAN model, was evaluated through a comparative analysis aimed at addressing the three key communication gaps identified in Chapter 2: (1) the lack of tools for post-development communication, (2) insufficient communication of emergent behaviors, and (3) the absence of systematic evaluations of communication effectiveness. To investigate Gaps 1 and 2, a content-based comparison was conducted between the outputs of ABM-VISTA and the ODD protocol documentation for the LUNTIAN model, presented in Chapter 4. As the most widely used standard for documenting and communicating agent-based models, the ODD protocol serves as a relevant benchmark. This comparison aims to assess how effectively each approach supports post-development transparency and conveys complex model dynamics. Gap 3, which pertains to evaluation practices, is addressed through a planned compar-

ative user study intended to establish a foundation for future empirical validation of communication effectiveness. Together, these analyses provide a comprehensive perspective on ABM-VISTA’s potential to overcome longstanding communication challenges in the field of agent-based modeling.

The student feedback directly shaped subsequent iterations of ABM-VISTA. For example, several participants requested a simplified summary view before examining the full operational flow, which led us to introduce layered levels of detail in both PMs and BPDs. Others highlighted the need for non-technical explanations, which motivated the integration of LLM-generated narratives. These refinements mark the transition from version 1.0 of ABM-VISTA (visualization only) to version 2.0 (visualization plus narrative), illustrating how the student evaluation was not only diagnostic but also formative in the development of the framework.

The comparative evaluation of ODD and ABM-VISTA was structured around three overarching communication dimensions: structural transparency, behavioral and dynamic transparency, and usability and accessibility. Each dimension was further broken down into sub-dimensions derived from both the agent-based modeling literature and the scoping review presented in Chapter 2. This structure allowed for a systematic assessment of how well each approach conveys different aspects of the LUNTIAN model.

Structural transparency refers to the clarity with which a model’s basic components — agent definitions and attributes, environmental setup, inter-agent interactions, state transitions, and parameter values — are communicated. ODD performed slightly better on this dimension due to its standardized format and detailed parameter documentation, which are particularly effective for replication and peer review. By contrast, ABM-VISTA focuses more on execution traces than parameter specification, leading to less emphasis on structural assumptions. Nonetheless, its visualizations significantly enhanced the communication of inter-agent interactions and decision rules, providing an empirical complement to ODD’s descriptive rigor.

Behavioral and dynamic transparency captures how well a communication method reveals the internal logic of the model over time, including temporal scheduling, decision sequencing, emergent behaviors, and execution traceability. This is where ABM-VISTA clearly outperformed ODD. By grounding its outputs directly in simulation runs, ABM-VISTA made visible the dynamic decision-making processes and emergent patterns — aspects that ODD, being static documentation, cannot fully capture. This dimension directly addresses Gap 2 identified in Chapter 2, highlighting ABM-VISTA’s potential to improve stakeholder understanding of complex system behaviors.

Usability and accessibility assess how understandable and useful the communication method is for both modelers and non-modelers, considering sub-dimensions such as purpose and rationale, accessibility to broader audiences, and standardization. ODD scored higher on standardization and formal rigor, reinforcing its role as a benchmark for scholarly documentation. However, ABM-VISTA provided clearer entry points for non-specialist stakeholders by combining visual and narrative forms, thereby increasing accessibility. This trade-off illustrates how the two approaches

serve different but complementary purposes: ODD ensures scientific robustness, while ABM-VISTA broadens interpretability and stakeholder engagement.

Together, these three dimensions highlight that ODD and ABM-VISTA are not substitutes but complements. ODD excels at documenting model intent and structure, while ABM-VISTA reveals what the model actually does in practice. Their combined use therefore provides a more holistic communication strategy, balancing formal transparency with dynamic interpretability.

5.3.2.1 Current Evaluation: Content-Based Comparison

To evaluate the communication utility of the ODD protocol (as used in Chapter 4 Section 4.2.3) and the ABM-VISTA outputs for the LUNTIAN model, the analysis was structured using a set of criteria informed by both the agent-based modeling literature and the scoping review presented in Chapter 2. Specifically, the analysis was organized around three overarching communication categories: structural transparency, behavioral and dynamic transparency, and usability and accessibility. These categories reflect common challenges and gaps identified in the literature – namely, the need to clarify internal model logic [Grimm 2006, Macal 2010], to better represent emergent and temporal dynamics [Bonabeau 2002, Railsback 2011], and to improve stakeholder understanding and engagement [Voinov 2010, Edmonds 2019].

Structural transparency captures how clearly a model’s components – such as agent types, interactions, the environment, and parameter settings – are described. This aligns with the “Structure” and “Complexity” themes coded in Chapter 2 (Section 2.4.4), which were frequently communicated through document-based approaches such as ODD. Behavioral and dynamic transparency refers to how well a model’s internal logic over time, including emergent outcomes and execution flow, is made visible to users. This corresponds directly to Gap 2 identified in Chapter 2 (Section 2.5.2), which highlights the limited support for communicating emergence and runtime behavior in current tools. Lastly, usability and accessibility focus on whether the model is understandable and useful to both modelers and non-modelers.

Taken together, these three dimensions offer a comprehensive and theoretically grounded basis for comparing traditional documentation methods such as ODD with newer, semi-automated tools like ABM-VISTA. They also reflect a shift from communication during model development to post-development interpretation – a shift emphasized in Gap 1 of Chapter 2 (Section 2.5.1). Table 5.2 presents a quantitative evaluation of the LUNTIAN model communication using these three dimensions. It summarizes performance across several sub-dimensions using a 5-point scale, where 5 indicates excellent performance and 1 indicates minimal or absent communication utility. The complete version of this table, with detailed justifications for each score, is provided in Appendix F.

The quantitative evaluation demonstrates how the ODD protocol and ABM-VISTA address different aspects of model communication in the LUNTIAN case. ODD scores slightly higher in structural transparency due to its formal structure

Table 5.2: Quantitative Evaluation of LUNTIAN Model Communication via ODD and ABM-VISTA [5 = Excellent; 4 = Good; 3 = Adequate; 2 = Limited; 1 = Absent or Minimal]

Dimension	Sub-dimension	ODD Score	ABM-VISTA Score
Structural Transparency	Agent definitions and attributes	5	4
	Environment setup	4	3
	Inter-agent interactions	3	5
	State transitions and rules	3	5
	Parameter values and assumptions	5	2
	<i>Average (Structural)</i>	4.0	3.8
Behavioral and Dynamic Transparency	Temporal scheduling and decision sequencing	3	5
	Emergent behavior	2	5
	Execution traceability	1	5
	<i>Average (Behavioral)</i>	2.0	5.0
Usability and Accessibility	Model purpose and rationale	5	3
	Accessibility to non-modelers	2	5
	Standardization and rigor	5	2
	<i>Average (Usability)</i>	4.0	3.3

and detailed parameter documentation. It provides a systematic account of agent definitions, environmental setup, and decision rules, making it well-suited for replication and peer review. However, because ODD relies on the modeler’s interpretation and selective emphasis during documentation, it is inherently prone to author bias. This subjectivity can obscure the actual behavior of the model once implemented, especially in terms of dynamic interactions and emergent phenomena. In contrast, ABM-VISTA derives its outputs directly from simulation traces, offering an execution-grounded perspective that reveals what actually occurred during model runs. By visualizing decision flows and behavioral sequences, it mitigates interpretive bias and strengthens the communicability of inter-agent dynamics, thereby enhancing accessibility for both modelers and stakeholders.

The most significant divergence appears in the dimension of behavioral and dynamic transparency. ABM-VISTA clearly outperforms ODD in this area by revealing how agents make decisions over time and how patterns such as illegal logging or trust breakdown emerge under different conditions. These simulation-based outputs directly address Gap 3 from Chapter 2: the limited attention to how models communicate emergence, one of the core strengths of agent-based modeling. While ODD describes the model’s intended logic, it remains static and does not convey how rules interact in context or how unexpected dynamics unfold. ABM-VISTA makes these emergent dynamics more legible through narrative summaries and process diagrams grounded in actual simulation runs.

Crucially, this comparison also highlights how ABM-VISTA contributes to closing Gap 1, which concerns the field’s predominant focus on communication during model development rather than post-development interpretation. ODD operates as a documentation tool typically prepared during or immediately after model construction. In contrast, ABM-VISTA enables post hoc explanation of model behavior, making it especially valuable for ABMs with limited or outdated documentation. By translating raw simulation logs into interpretable outputs, ABM-VISTA shifts communication toward what the model actually does, not just how it was intended to work. This post-development perspective, combined with its ability to surface emergent behaviors, positions ABM-VISTA as a vital complement to ODD – supporting a more holistic and layered model communication strategy.

5.3.2.2 Future Evaluation: Planned Comparative User Studies

To further validate the present findings and expand their generalizability, two empirical studies are proposed to address Gap 3 identified in Chapter 2 – the limited evaluation of how well model communication outputs support user comprehension, particularly regarding emergence. These studies aim to systematically assess how different model communication formats – ODD and ABM-VISTA – perform in terms of perceived clarity and actual understanding. The planned studies include: (A) a survey-based evaluation and (B) a comprehension-based performance task.

A. Planned Survey-Based Evaluation (Method A)

The first study will adopt a within-subjects survey design involving two participant groups: domain experts (e.g., forestry researchers, environmental planners) and stakeholder-analogue participants (e.g., students or NGO practitioners). Each participant will review two parallel descriptions of the LUNTIAN model – one following the ODD protocol and the other derived from ABM-VISTA outputs.

Participants will be asked to rate each version across five dimensions using Likert-scale items:

- Clarity (“I found this description easy to understand.”)
- Completeness (“This format provided sufficient information about the model.”)
- Helpfulness (“This helped me understand the simulator’s behavior over time.”)
- Confidence (“I feel confident about the model explanations.”)
- Preference (“I prefer this format over the other for learning about the model.”)

The survey will also collect demographic data and include open-ended prompts to capture qualitative feedback on user experience and communication effectiveness. This method is intended to elicit perceived strengths and weaknesses of each format from diverse users.

B. Planned Comprehension-Based Performance Task (Method B)

The second study will evaluate participants' actual comprehension through a task-based assessment. After reviewing each model version (ODD and ABM-VISTA), participants will respond to a series of objective and open-ended questions designed to assess their understanding of agent roles, decision logic, and emergent system behaviors. Sample questions may include: "Which agents are responsible for hiring labor?", "What happens when no harvesters are available?", and "What conditions trigger illegal activity in the model?"

Participant responses will be scored based on accuracy and depth, offering empirical evidence of how effectively each communication format conveys both foundational model mechanics and the emergent dynamics that are central to agent-based modeling. This approach aims to capture not only what participants remember but also how well they understand causal mechanisms and system-level outcomes.

Together with the planned survey (Method A), this comprehension task will triangulate the findings of the qualitative comparison presented in this chapter. The results are expected to inform future refinements of post-development communication tools like ABM-VISTA, ensuring that agent-based model outputs can meaningfully support user comprehension, stakeholder engagement, and evidence-informed decision-making.

5.4 Discussion

The application of ABM-VISTA to the LUNTIAN model yielded both encouraging results and notable limitations. Stakeholder evaluations and comparative analyses demonstrated that the framework can improve the interpretability of complex agent-based models, particularly through its automated narratives and process diagrams. However, challenges such as ambiguity in narrative outputs and the need for additional stakeholder guidance highlight areas for further refinement. This section situates these findings within the broader literature on participatory modeling and ABM communication. It examines how ABM-VISTA aligns with the communication categories outlined in Chapter 2, identifies its methodological contributions, and considers the implications of its application for future use in real-world SES contexts.

5.4.1 Scoping Review Alignment

The application of ABM-VISTA within the LUNTIAN case can be contextualized using the evaluative dimensions outlined in the scoping review (see Chapter 2): stakeholder participation, communication strategies, aspects of ABMs conveyed, and the intended purpose of communication. These categories frame the analysis of ABM-VISTA's strengths and limitations and are summarized in Table 5.3.

In terms of stakeholder participation, the ABM-VISTA framework primarily supported a nominal form of engagement. Visual diagrams aided participants in understanding the model's structure; while, stakeholder-oriented narratives targets

Table 5.3: Mapping of ABM-VISTA’s Application in LUNTIAN Against Scoping Review Categories

Category	Observations
Stakeholder Participation	Primarily nominal, as it focuses on presenting model structure and behavior in an accessible form. Limited representative participation occurs in cases where stakeholders are involved in verifying and/or improving the generated narrative descriptions.
Communication Approach	Multi-modal: visual (BPMN) and document-type (LLM-generated narratives, Simulation logs).
Aspects Conveyed	Model structure, complexity, and emergency are sufficiently captured , but not fully communicated.
Communication Purpose	Model presentation, transparency, and validation. May have potential for use in model reproducibility and extension work. Mainly explanatory and educational.

to assist in conveying emergent behaviors. A usability feedback session introduced an instrumental, consultative component; however, stakeholders were not involved in creating or adapting the agent-based model, thereby limiting deeper, co-creative participation. This constraint reflects both a practical limitation of the current implementation and a future opportunity to extend the framework toward more representative and transformative forms of participation.

From a communication perspective, ABM-VISTA employed a multi-modal strategy that combined BPMN diagrams, LLM-generated narratives, and structured simulation logs. These complementary formats offered accessible entry points for understanding system dynamics and agent interactions. Visual diagrams clarified temporal flow and interactions, while the narrative components translated simulation behaviors into language intelligible to non-specialist audiences. Although an interactive interface was not implemented in this case, the modular design of ABM-VISTA supports such extensions in future applications.

With regard to content, ABM-VISTA was able to convey agent behavior, temporal dependencies, and emergent dynamics. However, foundational model elements – such as structural hierarchies, underlying assumptions, and parameter rationales – were less explicitly communicated. Enhancing the visibility of these components will be crucial in contexts requiring greater model scrutiny, transparency, or stakeholder trust.

Finally, the primary purpose of communication in this application was explanatory, with a clear educational dimension. The outputs helped stakeholders grasp the internal logic of the simulation and facilitated learning in structured sessions.

Nonetheless, the framework has yet to be tested in contexts requiring persuasion, negotiation, or consensus-building. Given its structured and transparent outputs, ABM-VISTA holds strong potential to support such deliberative applications in the future.

5.4.2 Methodological Contributions

The integration of ABM-VISTA into LUNTIAN illustrates its methodological value in promoting model transparency. By converting simulation traces into visual diagrams and natural-language narratives, the framework enabled stakeholders to trace how agent decisions evolved over time and gave rise to emergent outcomes. This “glass-box” perspective contrasts sharply with the “black-box” nature often attributed to ABMs – particularly by non-experts – who may struggle to interpret internal model logic and dynamics.

A key strength of ABM-VISTA lies in its complementarity to formal modeling protocols such as the ODD framework. While ODD promotes scientific rigor through standardized documentation, it is typically authored by model developers immediately after (or during) model construction. As such, external stakeholders – including researchers, domain experts, and students – often depend entirely on these documents to interpret the model’s structure and behavior. ABM-VISTA enhances this process by enabling the independent extraction of structural and behavioral representations directly from simulation logs. This capability allows users to cross-validate ODD documentation, adding an additional layer of transparency and trust. Furthermore, in cases where formal documentation is absent, incomplete, or outdated, ABM-VISTA provides an accessible entry point for understanding model processes and emergent dynamics. In this way, it not only complements existing documentation but also broadens the interpretability and accessibility of agent-based models across diverse stakeholder groups and modeling contexts.

Implementing ABM-VISTA required an initial technical investment – developing custom simulation logging, integrating process mining tools, and refining prompts for LLMs. However, most of this work was a one-time setup. Once configured, the pipeline enabled automated and repeatable generation of visual and textual outputs, supporting consistent communication across simulation iterations. Crucially, because the structure of the simulation logs conforms to the generic format of event logs, the framework is easily adaptable to any modeling and simulation platform that can produce agent-level traces in this format. This platform-agnostic design enhances the portability and scalability of ABM-VISTA, making it a practical and reusable addition to the ABM toolkit for both researchers and practitioners.

5.4.3 Communication Outcomes and Broader Implications

Stakeholder feedback emphasized the value of ABM-VISTA’s visual and narrative outputs in enhancing comprehension and engagement. Visualizations clarified agent flows and interdependencies, while narratives translated technical events into di-

gestible accounts. Together, these modes lowered the cognitive barriers often associated with complex simulation models, particularly for stakeholders without a modeling background.

This addresses a well-documented gap in ABM practice: the difficulty of communicating non-linear, emergent, and distributed behaviors to diverse audiences. By transforming raw simulation data into communicable stories and structured visuals, ABM-VISTA enhances both the model transparency and accessibility. These improvements could potentially increase the adoption of ABMs applied in policy and decision-making – especially in complex, socio-environmental domains where stakeholder understanding and buy-in are crucial.

Nonetheless, the framework is not without limitations. Automated narratives may oversimplify or miss important nuances, particularly in models with asynchronous or recursive behaviors. The output quality also depends on the capabilities of the language model and the specificity of the prompt design. Improving flexibility and generalizability will be essential for future development. Enhancements might include modular log parsers, customizable user interfaces, and hybrid features that allow stakeholders to annotate, revise, or interact with outputs. These capabilities would not only increase adaptability but also deepen engagement and promote co-interpretation of model results.

5.4.4 Responsible Use of AI-Assisted Communication Tools

Deploying AI tools in participatory and community-facing settings also raises concerns about data ethics and responsible communication. This is addressed in ABM-VISTA by ensuring that no personal, private, or culturally sensitive data were included in prompts submitted to the language model. Input data consisted solely of simulation outputs, following principles of data minimization and privacy-by-design [Mittelstadt 2016, Morley 2020]. Even so, continued vigilance is put in place to ensure that generative AI does not inadvertently reveal or misrepresent sensitive dynamics in local contexts.

Ultimately, the ethical use of AI and modeling tools extends beyond deployment to questions of long-term accessibility and stewardship. ABM-VISTA and LUNTIAN are released under open-source licenses, with documentation to facilitate reuse and adaptation by local institutions and civil society organizations. Nonetheless, sustainable use depends on users' ability to interpret, maintain, and evolve the tools in line with changing needs. Future research should explore models of community ownership, capacity building, and co-maintenance to prevent tool abandonment or the reproduction of dependency cycles [Voinov 2010, Saltelli 2017].

5.5 Conclusion

This chapter demonstrated the application and evaluation of the ABM-VISTA framework as a post-development communication tool for agent-based models, using

the LUNTIAN model – a complex simulation of a forest-based socio-ecological system – as a case study. The evaluation, which combined stakeholder usability testing and a comparative analysis with the ODD protocol, revealed key strengths of ABM-VISTA. Participants from the initial student evaluation found its visual outputs intuitive, informative, and significantly more accessible than traditional documentation alone. While ODD excelled in documenting model structure and assumptions, ABM-VISTA provided superior transparency regarding behavioral flows and emergent phenomena – key features of ABMs that are often under-communicated.

Crucially, ABM-VISTA shifts the focus of communication from development-phase documentation to post-development interpretation. This is especially valuable in participatory or policy-oriented modeling contexts where stakeholders may not have technical expertise but still need to engage meaningfully with simulation results. The framework thus contributes not just a new tool, but a new orientation: from code and structure to interaction and insight.

Nonetheless, the approach is not without limitations. Visual complexity and occasional ambiguity in automatically generated narratives highlight the need for ongoing refinement, including layered interfaces and hybrid human-in-the-loop features. Additionally, broader and more diverse stakeholder evaluations are needed to validate the generalizability of the results.

Overall, this chapter advances the discourse on ABM communication by demonstrating how automated, execution-grounded tools can enhance interpretability, support stakeholder engagement, and ultimately increase the practical relevance of agent-based models in complex social-environmental systems. ABM-VISTA represents a promising step toward making ABMs not only more transparent, but more usable, explainable, and impactful beyond the research community.

Conclusion

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This dissertation set out to address a persistent yet underexplored challenge in agent-based modeling (ABM): how to support communication of complex simulation models to stakeholders, particularly during the post-development phase. While ABMs are powerful tools for simulating social-ecological systems (SES), their technical opacity often alienates non-expert stakeholders – undermining their practical utility and potential to inform real-world decisions. Bridging this gap between modelers and stakeholders requires not only better communication strategies, but also a reimagining of how models are designed, narrated, and evaluated for accessibility and trustworthiness.

The research unfolded in three major parts. First, a systematic scoping review of 65 scholarly articles was conducted to map the landscape of ABM communication strategies. This review revealed critical gaps in the literature: (1) communication practices are heavily skewed toward the development phase, with post-development communication largely neglected; (2) emergent behaviors – arguably the most interesting outputs of ABMs – are often insufficiently explained or presented for stakeholders; and (3) evaluations of communication effectiveness are sparse and methodologically inconsistent. These findings underscore the need for frameworks that treat communication not as a peripheral task but as a central, continuous component of the modeling lifecycle.

To help address some of the identified challenges, this dissertation introduces ABM-VISTA (Agent-Based Model - Visualization & Interpretation of Simulation Traces for Accessibility), a novel, semi-automated framework aimed at improving post-development communication. ABM-VISTA integrates simulation logging, process mining, and large language models (LLMs) to convert raw simulation traces into accessible visual and narrative representations. This approach reduces cognitive barriers and enhances model transparency making models accessible even for stakeholders (and users) who would be interested with the models. Importantly, ABM-VISTA moves beyond static documentation by enabling dynamic, stakeholder-friendly interpretations of model structure, processes, and emergent outcomes.

The third contribution is the design and application of LUNTIAN, a domain-specific ABM simulating the dynamics of an industrial tree plantation system in the Philippines. LUNTIAN integrates ecological, social, and economic agents, capturing the complexity of stakeholder interactions in a real-world SES context. Through its application, the utility of ABM-VISTA was preliminarily demonstrated. Initial stakeholder feedback informed its design and highlighted improvements in comprehension and accessibility. A content-based comparative analysis against the Overview, Design concepts, and Details (ODD) protocol further underscored its strengths in communicating emergent dynamics. Future usability testing and comparative user studies, as proposed in this dissertation, will be critical to empirically validate these findings and assess their generalizability.

Together, these contributions establish an end-to-end methodological pipeline – from diagnosis of communication shortcomings, to framework design, to empirical validation – that repositions communication as a scientifically rigorous and stakeholder-inclusive practice in ABM. The implications are substantial. By making simulation models more interpretable, ABM-VISTA supports the democratization of modeling insights, helping to eliminate the mutual understanding barrier that often prevents stakeholders from moving beyond passive observation. In doing so, it enables them to critically engage with complex system behaviors and actively participate in collective reflection and decision-making.

6.1 Future Research Directions

Advancing ABM-VISTA. Future research should expand ABM-VISTA’s capabilities along several technical dimensions. Full automation would reduce reliance on manual configuration, ensuring that model communication remains seamless even in highly complex SES contexts. Adaptive narrative generation – where explanations evolve dynamically depending on stakeholder expertise, context, or interaction – could further personalize communication and strengthen engagement. Finally, developing more interactive interfaces would allow stakeholders not only to read and visualize outputs, but to navigate models in real time, exploring causal relationships and emergent dynamics with greater agency.

Evaluating Stakeholder Impacts. While this dissertation confirms that ABM-VISTA enhances model accessibility and interpretability, the next critical step is to evaluate whether improved communication leads to tangible changes in model use and reuse, as well as in stakeholder decision-making and behavior. Such evaluation requires moving beyond comprehension studies toward participatory and longitudinal research. Key obstacles that may still hinder stakeholder involvement include: power imbalances between actors, entrenched institutional or political constraints, cognitive overload when navigating multiple layers of complexity, and differing priorities or time horizons among stakeholder groups. Explicitly investigating these factors will ensure that improvements in communication are meaningfully linked to

real-world outcomes.

Broader Perspectives. Beyond technical refinement and empirical validation, future work should also consider broader perspectives. Embedding ABM-VISTA into participatory governance processes across varied SES domains (e.g., water management, urban planning, biodiversity conservation) would test its scalability and generalizability. Cross-comparative studies between contexts could identify best practices and limits of the approach. Moreover, the ethical dimensions of model interpretation, AI integration, and long-term stakeholder empowerment demand continued reflection and adaptation.

6.2 Closing Reflections

In closing, this dissertation has examined how ABMs can be made more accessible, interpretable, and relevant for stakeholders. It began with a central question: how can the inherent complexity of social-ecological systems be communicated in ways that are both understandable and credible to diverse audiences? Addressing this question has revealed not only technical challenges but also methodological and ethical dimensions associated with making models transparent, trustworthy, and usable beyond the research community.

The contributions presented here suggest a reorientation in how ABM communication should be understood: not as a peripheral activity, but as a central and continuous component of the modeling lifecycle. The findings highlight transparency, interpretability, and stakeholder engagement as essential conditions for fostering the effective use and reuse of ABMs in research, policy, and practice. At the same time, this work underscores the need for further refinement. Future research should advance hybrid human–AI approaches, broaden stakeholder evaluations, and test these methods across a wider range of domains. Pursuing these directions will strengthen the capacity of ABMs to serve not only as representations of complex systems, but also as instruments for dialogue, collaboration, and informed decision-making.

Coding Schemes

This appendix presents the coding schemes used to analyze the literature corpus, as represented in the tables. Table A.2 outlines the classification of various forms of stakeholder participation identified in the reviewed articles, highlighting both levels and types of engagement. Table A.3 details the purposes for which models were communicated, providing definitions that contextualize each purpose within the scope of the study. Table A.4 catalogs the tools employed to communicate models to stakeholders, showcasing methods and approaches aimed at enhancing understanding and collaboration. Finally, Table A.1 describes additional categories related to ABM aspects conveyed to stakeholders, along with the evaluation of communication effectiveness.

Category	Classification	Definition	Theoretical basis
ABM aspects conveyed to stakeholders	Structure	The agents, their interrelationships, and the environment in which they operate.	[Macal 2010]; [Cenani 2021]
	Complexity	Interactions within the model.	
	Emergence	A phenomena characterized by non-linear and often unpredictable behaviors arising during simulations.	
Evaluation of the Effectiveness of Communicating ABM to Stakeholders	With Evaluation	The evaluation of the model's communication was described in the paper.	[Cartwright 2016]
	Planned Evaluation	The paper mentioned a plan for future evaluations.	
	Indirect Evaluation	The evaluation results were derived from the outcomes of another modeling activity (such as open discussions and post-game debriefings).	
	No Evaluation	There was no mention of the evaluation of the model's communication.	

Table A.1: Additional Coding Schemes

Classification	Definition	Theoretical basis	Example snippet
Nominal	Model communication is limited only to dissemination of research outcomes. Key point: “Communicate the ABM results”, “Present the simulation model”	Definition of “Form of Interest in Participation” adapted from [Van Bruggen 2019]	“... enhance the ability of subject matter experts and decision-makers to understand the results. ” [Barry 2008]
Instrumental	Model communication occurs only during consultations. Key point: “Gather empirical basis for ABM”, “Communicate to design the ABM”		“... These maps provide comprehensive insight analysis for later surveys and agent-based model creation. ” [Sinitetskaya 2020]
Representative	Model communication takes place during stakeholder dialogues and collaborative model development. In these interactions, stakeholders provide input and insights but do not have direct control over how the model is ultimately used. Key point: “Co-construction”, “Shared representation”		“... providing a shared representation of the current management of farms ” [Simon 2010]
Transformative	Model communication occurs through stakeholder dialogues and collaborative model-building. The primary aim of this participation is to empower stakeholders and foster a sense of ownership over the model. As a result, stakeholders are granted significant control over how the model is utilized. Key point: “ABM as a communication or exploratory tool”		“ an agent-based model is developed as a community communication tool in this study... to develop shared visions, assess barriers, and explore solution portfolios ” [Yang 2022]

Table A.2: Forms of model communication with stakeholders

Classification	Definition	Theoretical basis	Example snippet
Specification	Specification refers to a detailed description of how something should be done.	Open coding. codes identified during the course of literature review, guided by the [Dictionary 2024] definition of the main keyword.	“The process of participatory modelling involves farmers and agricultural experts in designing the agent-based model... ” [Smetschka 2020]
Transparency	Transparency is the quality of being easily understood or visible.		“... stakeholders need to understand them in order to assume ownership of the model and to criticize it.” [Bommel 2011]
Validation	Validation is the process of ensuring something is officially acceptable or approved.		“... games for information validation may be designed and used to re-engage stakeholders even though the model is not yet finished.” [Shelton 2018]
Presentation	Presentation refers to the act of showing something to an audience.		“... aid in the understanding of these systems and for presentation of results to decision-makers.” [Barry 2008]
Reproducibility	Reproducibility means that an experiment can be repeated with the same results.		“... a better means of communication among users or tools ... should also facilitate model replication. ” [Sansores 2006]
Extension	Extension refers to expanding the scope or adding new elements to something.		“... better communicate, to more easily identify the model’s similarities and facilitate the reuse and extension of existing software models. ” [Thomas-Vaslin 2013]

Table A.3: Purposes of communicating the model with stakeholders

Classification Definition		Theoretical basis	Example snippet
Document-type	Description of an ABM in narrative or written form. Key point: “Description of the conceptual design”, “Details of the implementation”	Open coding. codes were identified during the course of literature review.	“TRACE documents are meant to provide comprehensive documentation of models that can be submitted as supplementary material with scientific publications , reports, or dossiers where models are presented to support decision making.” [Ayllón 2021]
Visual	Representation of an ABM in a graphical form. Key point: Visualization, Diagrams		“The diagrams build on the recognition that the workings of an ABM can only be understood through the behavior of the agents, and that the behavior of the agents can only be understood through their percepts, objectives, and actions... Their strength lies in the fact that they visualize the relevant elements and clarify how these are interrelated by explicitly stating their relationships.” [Hall 2016]
Interactive	Representation of an ABM that allow stakeholder to interact with the model. Key point: Participatory, Gamified		“We also aim to stimulate the participants’ thinking and co-learning through the collective exploration of scenarios of varying water and labor availability, with the ultimate goal of further strengthening their adaptive management ability throughout this very interactive participatory modeling and simulation process .” [Naivinit 2010]

Table A.4: Kinds of tools used to communicate model with stakeholders

Tree Behavior References

This appendix presents the compiled empirical and literature sources, and equations used to model LUNTIAN.

Table B.1: Parameter sources and literature references for modeling *Swietenia macrophylla*

Modeled Tree Behavior	Tree Parameters and/or Traits	Reference(s)
Growth	DBH Increment	Shono, K., & Snook, L. K. (2006). Growth of big-leaf mahogany (<i>Swietenia macrophylla</i>) in natural forests in Belize. <i>Journal of Tropical Forest Science</i> , 18(1), 66–73.
	DBH Size classes	Coracero, E. E. (2023). Distribution and Management of the Invasive <i>Swietenia macrophylla</i> King (Meliaceae) at the Foot of a Protected Area in Luzon Island, Philippines. <i>Journal of Zoological and Botanical Gardens</i> , 4(3), 637–647. https://doi.org/10.3390/jzbg4030045
	Effects of neighborhood interaction	Yue, Q., Geng, Y., von Gadow, K., Fan, C., Zhang, C., & Zhao, X. (2022). Effects of neighborhood interaction on tree growth in a temperate forest following selection harvesting. <i>Ecological Indicators</i> , 136, Article 108663. https://doi.org/10.1016/j.ecolind.2022.108663
Mortality	Shade tolerance, DBH	Nguyen, H., Vanclay, J., Herbohn, J., & Firn, J. (2016). Drivers of Tree Growth, Mortality and Harvest Preferences in Species-Rich Plantations for Smallholders and Communities in the Tropics. <i>PLOS ONE</i> , 11(10), e0164957. https://doi.org/10.1371/journal.pone.0164957
Recruitment	DBH	Grogan, J., Landis, R. M., Free, C. M., Schulze, M. D., Lentini, M., & Ashton, M. S. (2014). Big-leaf mahogany <i>Swietenia macrophylla</i> population dynamics and implications for sustainable management. <i>Journal of Applied Ecology</i> , 51(3), 664–674. https://doi.org/10.1111/1365-2664.12210

Table B.2: Parameter sources and literature references for modeling Dipterocarp species

Modeled Tree Behavior	Tree Parameters and/or Traits	Reference(s)
Growth	DBH Increment	Nguyen, T. T. (2009). Modelling Growth and Yield of Dipterocarp Forests in Central Highlands of Vietnam. Ph.D. Dissertation, München: Technische Universität München.
	DBH Size classes	Galias, D. C., & Cuevas, V. C. (2018). The regenerating forest of Magbukún Aeta in Morong, Bataan, Philippines: A biological hotspot for protection and conservation. <i>Philippine Journal of Systematic Biology</i> , 12(1), 77–102. https://doi.org/10.26757/pjsb.2018a12002
	Effects of neighborhood interaction	Yue, Q., Geng, Y., von Gadow, K., Fan, C., Zhang, C., & Zhao, X. (2022). Effects of neighborhood interaction on tree growth in a temperate forest following selection harvesting. <i>Ecological Indicators</i> , 136, Article 108663. https://doi.org/10.1016/j.ecolind.2022.108663
Mortality	Stand basal area	Nguyen, T. T. (2009). Modelling Growth and Yield of Dipterocarp Forests in Central Highlands of Vietnam. Ph.D. Dissertation, München: Technische Universität München.
Recruitment	Stand basal area, Count of new Dipterocarp trees	Nguyen, T. T. (2009). Modelling Growth and Yield of Dipterocarp Forests in Central Highlands of Vietnam. Ph.D. Dissertation, München: Technische Universität München.

Table B.3: Equations for modeling tree dynamics

Modeled Tree Behavior**Growth.**

$$DBH_t(n) = DBH_{t-1}(n) + Growth_{rate} \cdot Growth_coef(\{water, soil_pH, temp\}) \cdot NI$$

where,

$$Growth_coef(\min, \max, \text{curr}) = \begin{cases} \frac{\text{curr}}{\text{ave} - \min} + \frac{\min}{\min - \text{ave}}, & \text{curr} \leq \text{ave}, \\ -\left(\frac{\text{curr}}{\max - \text{ave}} + \frac{\max}{\max - \text{ave}}\right), & \text{curr} > \text{ave}. \end{cases}$$

and the Neighborhood Influence (NI) is given by

$$NI_n = \sum_{\substack{i=1 \\ i \neq n}}^I \frac{BA_i \times Dn,i}{dist_{n,i}}$$

where:

- $dist_{n,i}$ refers to the spatial distance from focal tree n to neighboring tree i ,
- BA_i represents the basal area of the neighbor,
- I is the total number of neighbors,
- Dn,i is the pairwise biological dissimilarity between the focal tree n and neighbor i .

Mortality.

$$\ln\left(\frac{P_{\text{dead}}}{P_{\text{survival}}}\right) = -2.917 - 1.897 \times is_shade_tolerant - 0.079 \times DBH$$

Recruitment.

$$\text{1-year-old seedlings} = \sum_{i=1}^n \text{fruit}_i \cdot s_{\text{fruit}} \cdot f_{\text{surv}} \cdot f_{\text{gap}} \cdot f_{\text{viable}}$$

where n is the number of reproductive trees in the population, fruit_i is the number of fruit produced by tree i , s_{fruit} is the mean number of viable seeds per fruit, f_{surv} is the fraction of seeds that germinate and survive to become 1-year-old seedlings, f_{gap} is the fraction of the landscape in canopy gaps exclusive of logging, and f_{viable} is the fraction of gap area viable for recruitment.

Table B.4: Parameter sources and literature references for computing labor and maintenance costs on a 35-year cutting cycle (as set by [Department of Environment and Natural Resources (Philippines) 1992])

	Reference(s)
Nursery Management	ERDB (Ed.). (2015). Mass Propagation and Nursery Management of Dipterocarps. DENR Recommends. https://erdb.denr.gov.ph/wp-content/uploads/2015/06/denr_v6.pdf
Harvesting	Calderon, M.M., & Nawir, A.A. (2006). An evaluation of the feasibility and benefits of forest partnerships to develop tree plantations: Case studies in the Philippines. Center for International Forestry Research (CIFOR). https://doi.org/10.17528/cifor/002139
Plantation Development and Assisted Natural Regeneration	Calderon, M.M., & Nawir, A.A. (2006). An evaluation of the feasibility and benefits of forest partnerships to develop tree plantations: Case studies in the Philippines. Center for International Forestry Research (CIFOR). https://doi.org/10.17528/cifor/002139

LLM-Generated Narratives and LLM-as-Judge

C.1 LLM-Generated Narratives

C.1.1 Mistral 24b

Comprehensive Narrative Overall Purpose and Mechanism. The agent-based model appears to simulate the behavior of individuals (people) in response to an infectious process. The simulation begins with the START event, which triggers the `_internal_init31` task executed by `model6_model`. This initialisation leads directly to the stay state for the people actor. From the stay state, individuals can transition to either the infect or move states. The infect state represents a scenario where an individual becomes infected and has a high likelihood (0.8013) of staying in that state. However, there is also a low likelihood (0.1987) of moving from the infect state to the move state. The move state indicates that individuals are mobile and can transition back to the infect state with a moderate likelihood (0.4369) or stay in the stay state with a similar likelihood (0.4517). The stay state allows for transitions back to either the infect or move states, with moderate and low likelihoods respectively. Probable Applications This model can be applied in various real-world and theoretical contexts:

1. Epidemiology: Simulating the spread of infectious diseases within a population.
2. Urban planning: Understanding how mobility patterns affect disease transmission.
3. Public Health Policy: Evaluating the effectiveness of interventions that encourage staying at home versus moving around.

Key Insights and Takeaways

- Initialization Phase: The model starts with an initialisation phase (`_internal_init31`) that sets individuals to a stay state, suggesting a controlled or quarantined starting condition.
- Infection Dynamics: The high likelihood of staying in the infect state indicates that once infected, individuals are likely to remain so for some time.

- **Mobility Impact:** The moderate transition probabilities between move, stay, and infect states highlight the complex interplay between mobility and infection risk.
- **End State:** The absence of a direct transition from infect to END (weight = 0.0) suggests that the model does not account for recovery or removal from infectious state, which could be a limitation.

Overall, this agent-based model provides a framework for understanding how individual behaviors and transitions between states can influence the spread of an infection within a population. The insights gained can inform strategies to mitigate disease transmission by adjusting mobility patterns and intervention measures.

C.1.2 Gemini 2.0 Flash

Comprehensive Narrative of the Agent-Based Model. The ‘Luneray-act’ simulation model appears to be an agent-based model designed to simulate the spread or dynamics of a state (potentially an infection, an idea, or a resource) within a population of agents represented by the people actor. The model begins with an initialization phase orchestrated by the model6_model actor, where both the overall simulation environment and the individual agents undergo a setup process. Following this, the agents enter a ‘stay’ phase, which could represent their baseline state or location. The core mechanism of the model revolves around the transitions between three key states for the agents: ‘infect’, ‘move’, and ‘stay’. An agent in the ‘infect’ state is highly likely to remain in that state. However, there’s a smaller chance they might move. Notably, there’s no direct transition from ‘infect’ to ‘END’ based on the provided information, implying that the termination of an agent’s involvement might be governed by other conditions or a sequence of states not fully captured by these direct transitions. Movement plays a crucial role in the dynamics. Agents that are moving have a significant probability of becoming infected, suggesting that movement brings them into contact or proximity with factors that can cause the transition to the ‘infect’ state. Conversely, moving agents are also likely to settle into a ‘stay’ phase. Even without moving, agents in the ‘stay’ state face a considerable risk of becoming infected, possibly due to local interactions or exposure within their current state or location. From the ‘stay’ state, there’s a smaller chance of an agent initiating movement. The ‘END’ event signifies the termination of an agent’s active participation in the simulation. The fact that there is no direct path to ‘END’ from ‘infect’ suggests that recovery, removal, or another condition must be met before an agent reaches this state. Probable Applications: This model structure is highly reminiscent of epidemiological models simulating the spread of infectious diseases. The ‘infect’ state clearly maps to being infected, ‘move’ could represent the movement of individuals within a population, and ‘stay’ could represent being in a specific location or social group. The transition probabilities would then represent factors like transmission rates during contact (implied in move to infect and stay to infect), recovery rates (potentially leading to ‘END’ through

other paths), and mobility patterns. However, the model could also be applied to other domains:

- Diffusion of Innovation/Ideas: ‘Infect’ could represent the adoption of a new idea, ‘move’ could represent the spread of information through a network, and ‘stay’ could represent a period of maintaining the current status.
- Resource Contagion: ‘Infect’ could represent the acquisition of a resource, ‘move’ could represent agents seeking resources, and ‘stay’ could represent agents utilizing the resource in a specific location.
- Behavioral Contagion: ‘Infect’ could represent the adoption of a certain behavior, with movement facilitating interaction and potential adoption.

Key Insights and Takeaways:

- Persistence of the ‘Infected’ State: Once an agent is ‘infect’ed, they are likely to remain so, highlighting the potential for a sustained presence of the state within the population.
- Mobility as a Risk Factor: Movement significantly increases the probability of becoming ‘infect’ed, underscoring the role of interaction and contact in the spread of the simulated phenomenon.
- Local Transmission: The substantial probability of transitioning from ‘stay’ to ‘infect’ indicates that even without movement, there are mechanisms for the state to spread within a local context.
- ‘END’ State Dynamics: The absence of a direct infect to END transition suggests that the process of leaving the simulation (e.g., recovery, attrition) is not a direct consequence of being in the ‘infect’ed state alone and likely involves other factors or a sequence of transitions not immediately apparent.
- Importance of Initial Conditions: The deterministic transitions from START to `_internal_init31` to stay highlight the importance of the initial setup in influencing the subsequent dynamics of the simulation.

In conclusion, the ‘Lunera-act’ model appears to be a dynamic agent-based simulation focused on the spread or maintenance of a state (‘infect’) within a population of agents who can move and stay. The transition probabilities define the likelihood of moving between these states and the risk of becoming ‘infected’ under different conditions. Further understanding of what the ‘END’ state represents and the specific meaning of ‘infect’, ‘move’, and ‘stay’ within the intended application would provide even deeper insights into the model’s behavior and implications.

C.1.3 Claude 3.7 Sonnet

Comprehensive Narrative Model Purpose and Mechanism. “Lunera-act” is an agent-based model simulating infectious disease transmission in a population. The model captures how disease spreads based on individual movement patterns and social interactions. Its core mechanism revolves around the infection dynamics influenced by mobility decisions (stay vs. move) of individuals. The simulation starts with initialization, after which individuals follow a stochastic process moving between three primary states: staying in place, moving to new locations, and potentially becoming infected or infecting others. The probabilities governing these transitions appear calibrated to reflect realistic disease spread patterns where mobility influences transmission risk. Probable Real-World Applications

This model would be valuable for:

1. Epidemic forecasting: Predicting how infectious diseases spread through communities
2. Public health intervention planning: Testing effectiveness of movement restrictions, quarantine strategies, or vaccination programs
3. Urban planning: Understanding how city design and population density affect disease spread
4. Transportation policy: Evaluating how mobility patterns impact public health outcomes
5. Disaster response planning: Preparing for containment strategies during outbreaks

Key Insights and Takeaways

1. Mobility is a key factor in disease transmission: The high probability of infection after movement (43.69%) compared to staying (42.13%) demonstrates how mobility patterns directly influence disease spread.
2. Post-infection behavior change: After infection, individuals predominantly stay in place (80.13%), which could represent: Self-isolation due to symptoms; Mandated quarantine measures; Reduced mobility due to illness
3. Spatial clustering effects: The significant probability of infection during “stay” states suggests proximity-based transmission within local clusters.
4. Continuous cycle: The model shows disease transmission as an ongoing process rather than a one-time event, reflecting the realistic nature of epidemic progression.
5. Intervention potential: The clearly identified transition probabilities provide potential points for intervention strategies—specifically targeting high-probability pathways to reduce disease spread.

This model demonstrates how relatively simple agent-based rules can generate complex, emergent patterns of disease transmission that mirror real-world epidemic dynamics. Its structure would allow researchers and policymakers to test various intervention strategies by modifying the transition probabilities between states.

C.2 LLM-as-Judge: GPT-4

C.2.1 Prompt

You are “JudgeGPT,” an expert in simulation modelling and agent-based systems. Your task is to evaluate three candidate narratives (Mistral 24b, Gemini 2.0 Flash, Claude 3.7 Sonnet) that were written in response to this original task prompt and model description:

“You are provided with detailed descriptions of a complete simulation execution for an agent-based model. Your task is to: Develop a comprehensive narrative that explains the overall purpose and mechanism of the agent-based model, the probable applications of the model in real-world or theoretical contexts, and the key insights and takeaways derived from the analysis of interactions and transitions. Below are the descriptions: According to the business process diagram of the simulation model ‘Luneray-act’. The simulation model involves 2 actors: model6_model, and people. Actor ‘model6_model’ executes the following processes: ‘_internal_init31’ task, and ‘START’ event. The following are the process executions involving actor ‘people’. ‘START’ followed by ‘_internal_init31’. It also interacts with the actor ‘people’ through the execution of ‘_internal_init31’ followed by ‘stay’. Actor ‘people’ executes the following processes: ‘infect’ task, ‘stay’ task, ‘END’ event, and ‘move’ task. The following are the process executions involving actor ‘people’: ‘infect’ followed by ‘END’ or ‘move’ or ‘stay’, ‘move’ followed by ‘infect’ or ‘stay’, ‘stay’ followed by ‘infect’ or ‘move’. In total, there are 4 processes in the model: infect, stay, move, _internal_init31, and START. To better understand how the model executes, provided below is a description of the same simulation model derived from its graph representation. The nodes of the graph represents the processes that are executed in the model. For this simulation model, the nodes are: END, START, _internal_init31, infect, move, and stay. On the other hand, the edges represents the transition from one process execution to another, with the weight describing the likelihood of the transition. For this simulation model, the edges are: START to _internal_init31 (weight = 1.0), _internal_init31 to stay (weight = 1.0), infect to END (weight = 0.0), infect to move (weight = 0.1987), infect to stay (weight = 0.8013), move to infect (weight = 0.4369), move to stay (weight = 0.4517), stay to infect (weight = 0.4213), and stay to move (weight = 0.1558).”

— Use the six evaluation metrics below to assign each Mistral 24b score from **1 (lowest)** to **5 (highest)**. Then, for each metric, write a one-sentence justification. Finally, give an overall ranking (1st, 2nd, 3rd) with a brief wrap-up comment.

Evaluation Metrics

- Precision** - Does the narrative’s description of actors, processes, and transition weights exactly match the provided model details?

2. **Coverage** - Does the narrative mention and integrate *all* key elements (actors, processes, graph nodes, weighted transitions)? 3. **Faithfulness** - Does it avoid introducing any facts or causal claims *not* grounded in the description (no hallucinations or contradictions)? 4. **Interpretive Depth** - Does it uncover or explain underlying causal or emergent patterns (e.g. feedback loops, high-risk paths)? 5. **Novelty of Insight** - Does it go beyond restating the data to propose creative applications, limitations, or broader contexts? 6. **Clarity** - Is the narrative logically structured, easy to follow, and free of ambiguous language? —

C.2.2 Result

Across three independent re-evaluations, Gemini 2.0 Flash consistently ranks first (strongest depth and novelty), Mistral 24B second (high precision and clarity), and Claude 3.7 Sonnet third (clear but lacking some coverage and precision). The tables below present the detailed results of the evaluation.

Table C.1: Round 1. Mistral 24b

Metric	Score	Justification
Precision	5	Every actor, process, and exact transition weight (including zero for infect→END) is correctly stated.
Coverage	5	Mentions all six nodes (START, __internal__init31, stay, infect, move, END) and all weighted edges.
Faithfulness	5	No unsupported facts or contradictions—fully grounded in the prompt.
Interpretive Depth	4	Identifies infection persistence and mobility interplay but doesn't explore deeper feedback loops.
Novelty of Insight	4	Points out the missing infect→END link but otherwise stays within standard epidemiological framing.
Clarity	5	Follows a clear, logical structure: initialization → transitions → applications → insights.

Table C.2: Round 1. Gemini 2.0 Flash

Metric	Score	Justification
Precision	4	Describes relative likelihoods but fails to repeat the exact numeric weights for every edge.
Coverage	5	Addresses all actors, states, transitions, and even implicit END dynamics.
Faithfulness	5	Contains no hallucinations—everything traces back to the description.
Interpretive Depth	5	Uncovers nuanced patterns (implicit termination, local vs. global spread).
Novelty of Insight	5	Broadly generalizes to ideas diffusion, resource contagion, behavioral spread.
Clarity	4	Very detailed; a few sentences about END dynamics read densely.

Table C.3: Round 1. Claude 3.7 Sonnet

Metric	Score	Justification
Precision	4	Correctly cites the two largest transition percentages but omits a couple of the smaller numeric weights.
Coverage	3	Leaves out the zero-weight infect→END and doesn't mention stay→move weight explicitly.
Faithfulness	5	Aligns perfectly with provided facts—no invented details.
Interpretive Depth	4	Highlights mobility's impact and clustering but doesn't probe deeper emergent loops.
Novelty of Insight	4	Good on intervention points but remains firmly in public-health territory.
Clarity	5	Exceptionally well organized into purpose, applications, and takeaways.

Table C.4: Round 2. Mistral 24b

Metric	Score	Justification
Precision	5	Exactly matches all actors, processes, and weights including the zero-value link.
Coverage	5	Fully covers nodes and all nine edges with their weights.
Faithfulness	5	Sticks strictly to the prompt, no extraneous information.
Interpretive Depth	4	Recognizes key infection and mobility trade-offs, but lacks deeper systemic patterns.
Novelty of Insight	4	Notes limitation around no recovery, but otherwise conventional.
Clarity	5	Clear sections and smooth narrative flow.

Table C.5: Round 2. Gemini 2.0 Flash

Metric	Score	Justification
Precision	4	Communicates transition ideas but doesn't recite every numeric weight.
Coverage	5	Covers all states, edges, and even speculates on END's implicit conditions.
Faithfulness	5	No invented processes—everything grounded in the given description.
Interpretive Depth	5	Explores implicit loops and termination conditions, showing causal sophistication.
Novelty of Insight	5	Applies the model to domains well beyond epidemiology.
Clarity	4	Dense in places, especially around END interpretations.

Table C.6: Round 2. Claude 3.7 Sonnet

Metric	Score	Justification
Precision	4	Reports major probabilities accurately but misses some smaller weights.
Coverage	3	Omits the zero-weight infect→END and does not list stay→move explicitly.
Faithfulness	5	Only uses facts from the prompt; no contradictions.
Interpretive Depth	4	Captures mobility and clustering but not deeper emergent behaviors.
Novelty of Insight	4	Solid intervention suggestions but conventional overall.
Clarity	5	Very well structured and readable.

Table C.7: Round 3. Mistral 24b

Metric	Score	Justification
Precision	5	All actors, processes, and numeric weights (including infect→END=0) are correct.
Coverage	5	References each of the six nodes and every transition edge.
Faithfulness	5	Fully faithful—no hallucinations or contradictions.
Interpretive Depth	4	Points out infection persistence and mobility interplay, but no deeper emergent structure.
Novelty of Insight	4	Mentions the lack of recovery path but stays within typical epidemic framing.
Clarity	5	Crystal-clear progression from mechanics to insights.

Table C.8: Round 3. Gemini 2.0 Flash

Metric	Score	Justification
Precision	4	Correct on structure and probabilities in prose, but doesn't enumerate every number.
Coverage	5	Mentions all states, transitions, and even speculates on implicit END dynamics.
Faithfulness	5	No invented elements—everything is rooted in the prompt.
Interpretive Depth	5	Reveals implicit feedback and causal pathways, showing strong systemic insight.
Novelty of Insight	5	Broadly generalizes to multiple contagion domains beyond disease.
Clarity	4	Highly detailed; small sections on END dynamics could be streamlined.

Table C.9: Round 3. Claude 3.7 Sonnet

Metric	Score	Justification
Precision	4	Correctly gives the two most significant percentages but omits smaller ones like stay→move or infect→move.
Coverage	3	Does not explicitly cover the zero-weight infect→END or all nine edges.
Faithfulness	5	No contradictions—remains true to given data.
Interpretive Depth	4	Good on clustering and post-infection behavior but lacks deeper emergent analysis.
Novelty of Insight	4	Offers clear intervention points but within the usual public-health lens.
Clarity	5	Well organized into distinct sections, very easy to follow.

LUNTIAN Model

Visualizations

This appendix presents the business process diagrams illustrating the processes executed by each agent in the model.

D.1 Biophysical Agents



Figure D.1: Road - BPD

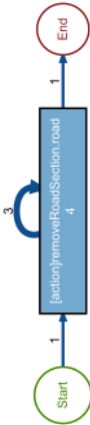


Figure D.2: Road - PM



Figure D.3: Soil - BPD

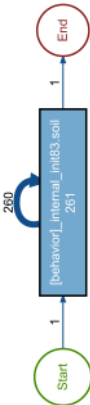


Figure D.4: Soil - PM

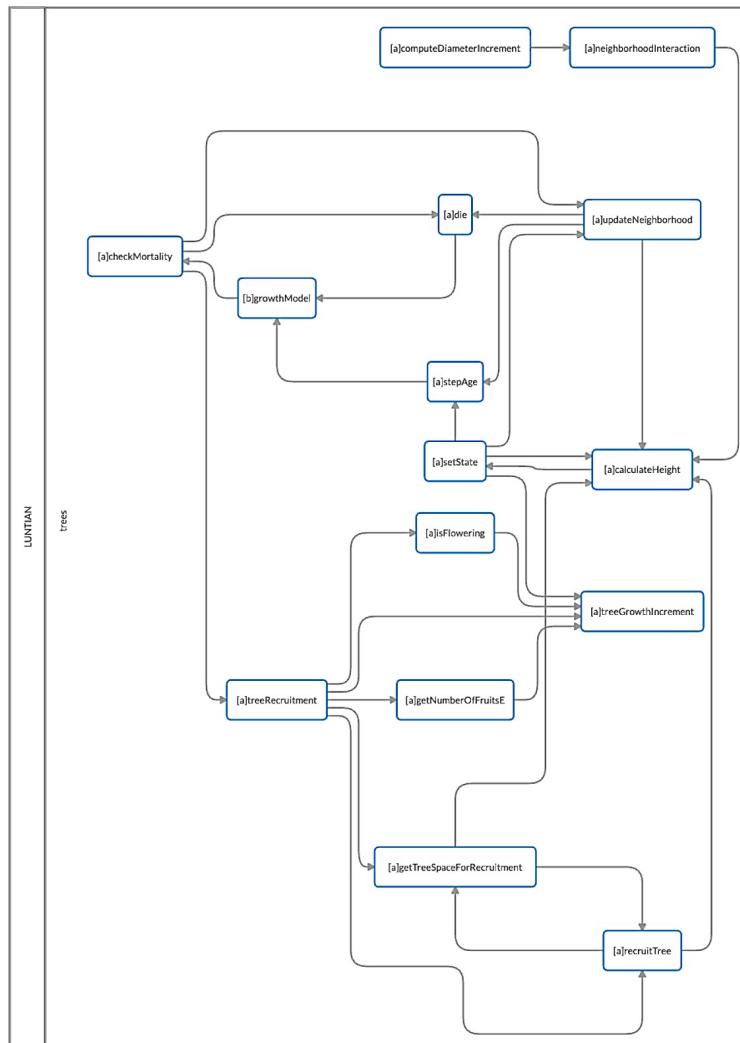


Figure D.5: Trees - BPD

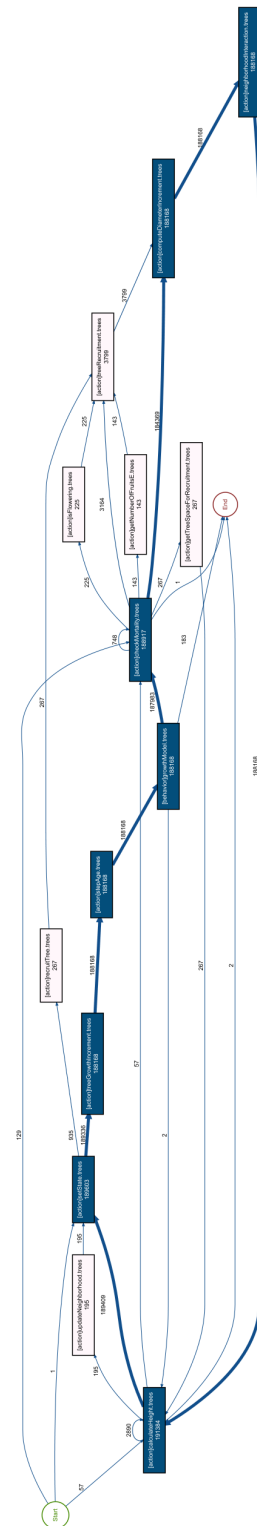


Figure D.6: Trees - PM

D.2 Social Agents

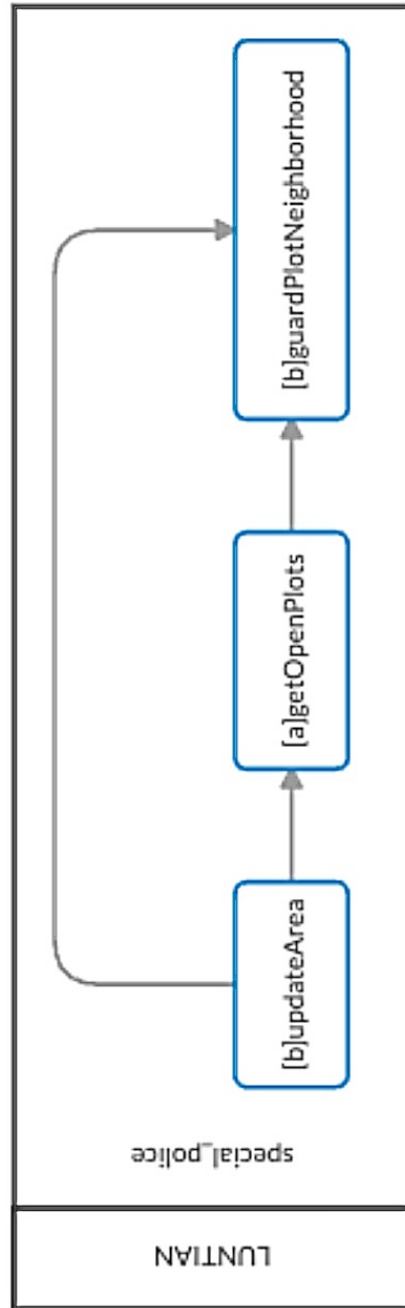


Figure D.7: Special Police - BPD

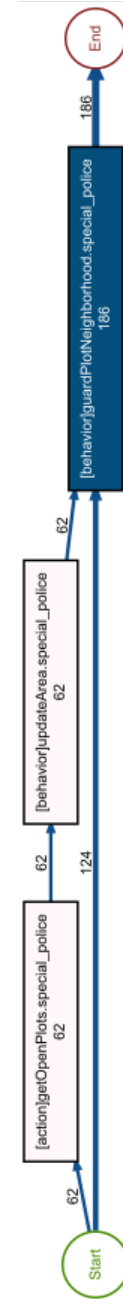


Figure D.8: Special Police - PM

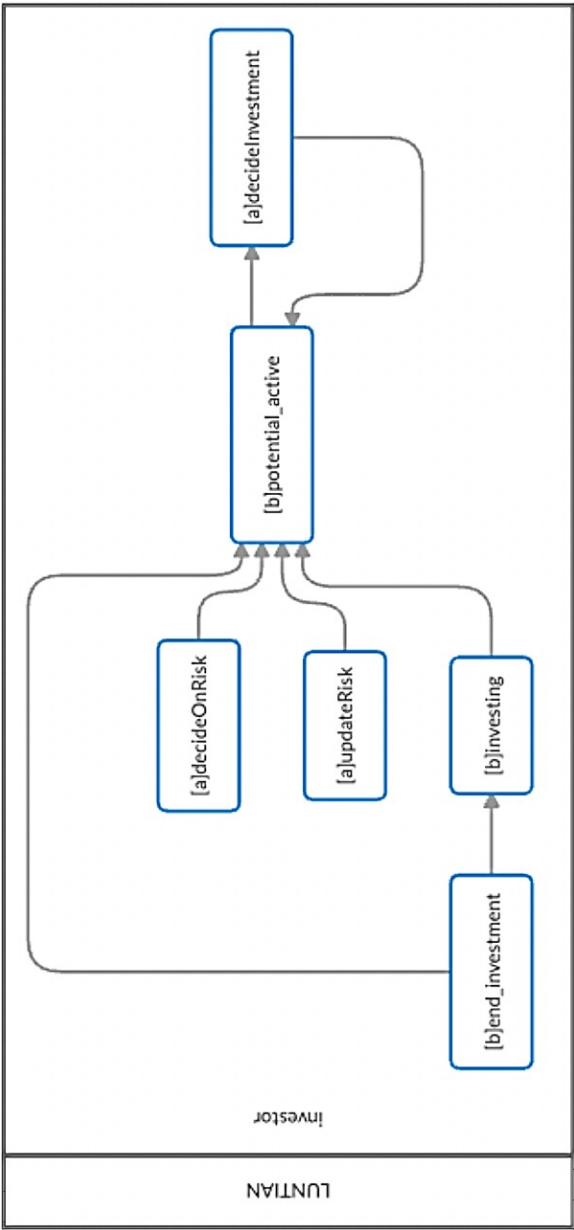


Figure D.9: Investor - BPD

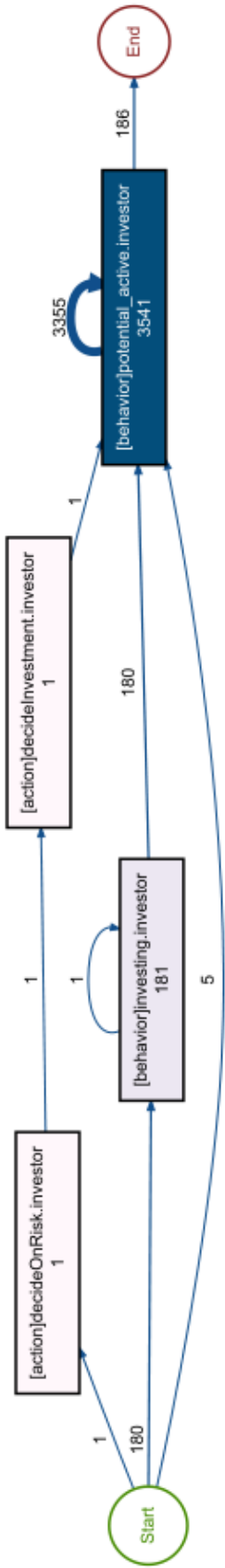


Figure D.10: Investor - PM

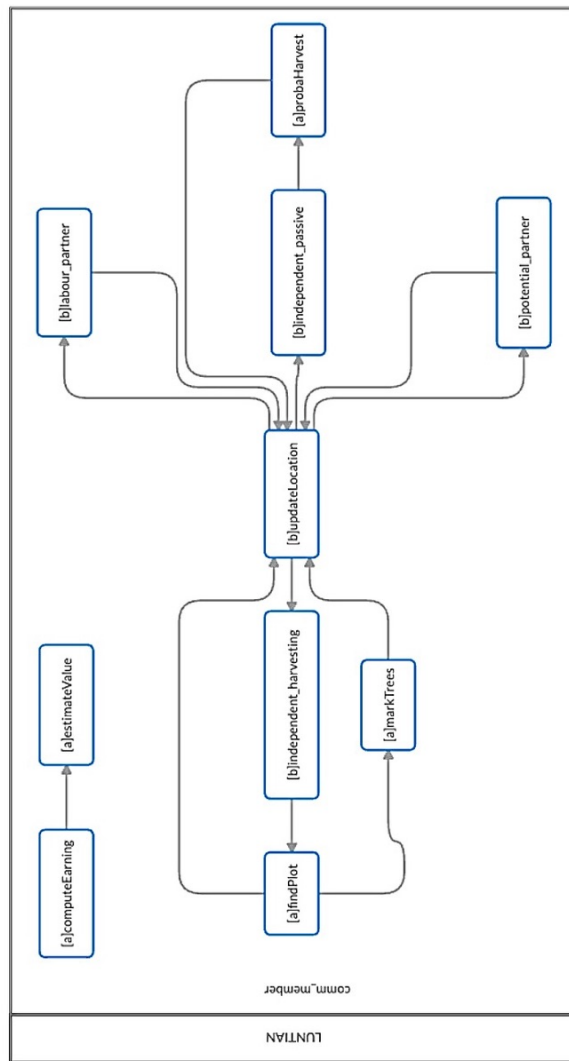


Figure D.11: Community Member - BPD

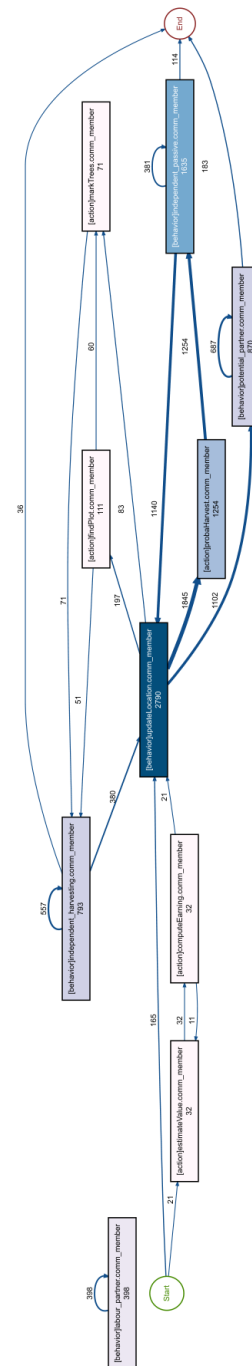


Figure
Community
ber - PM

D.12:
Mem-

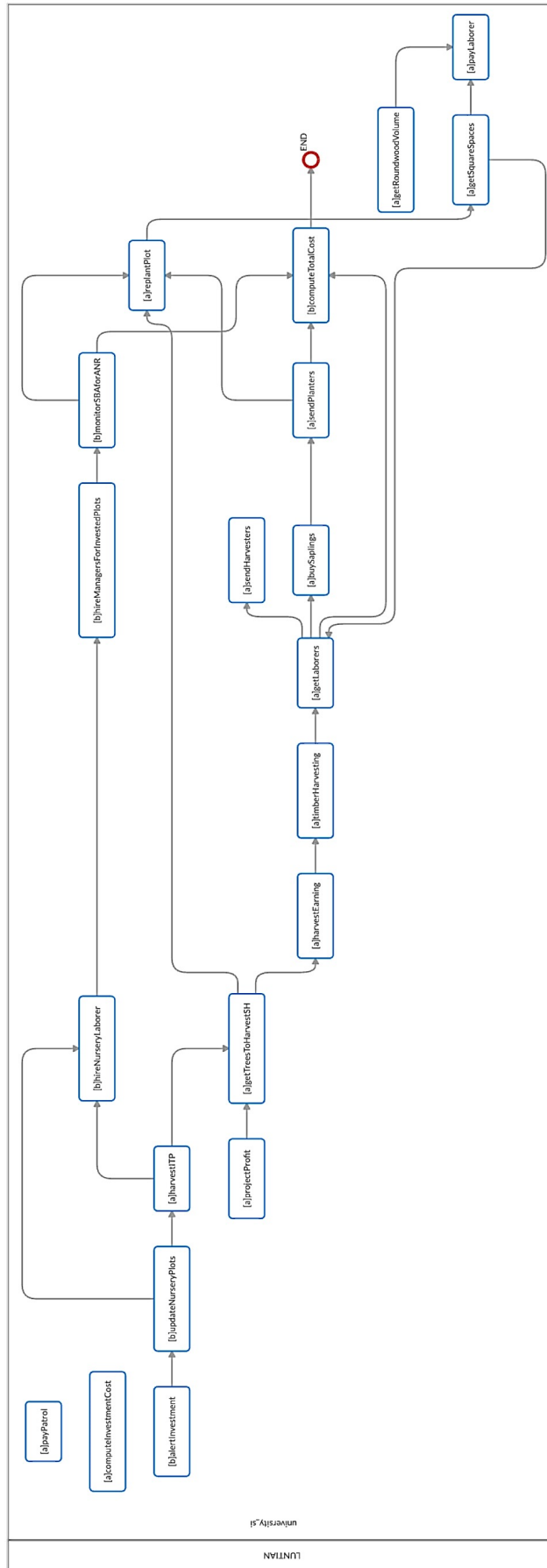


Figure D.13: University - BPD

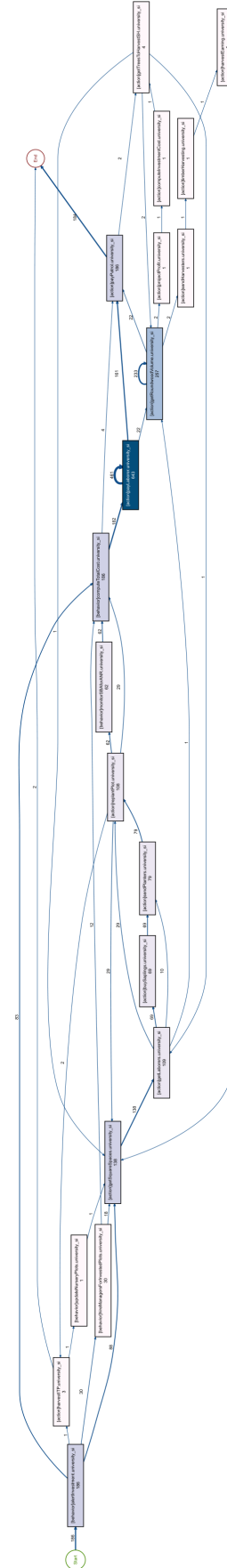


Figure D.14: University - PM

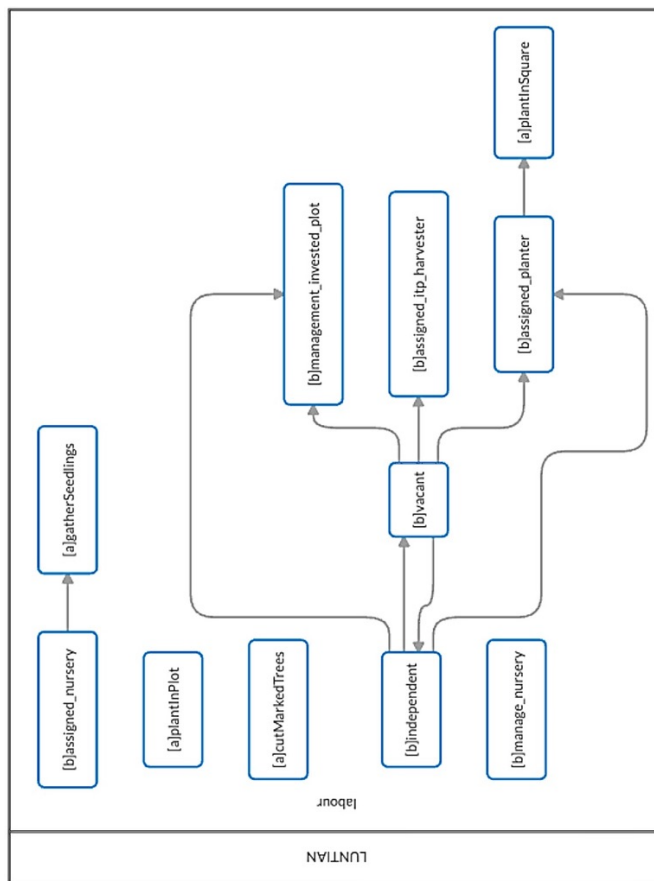


Figure D.15: Labour - BPD

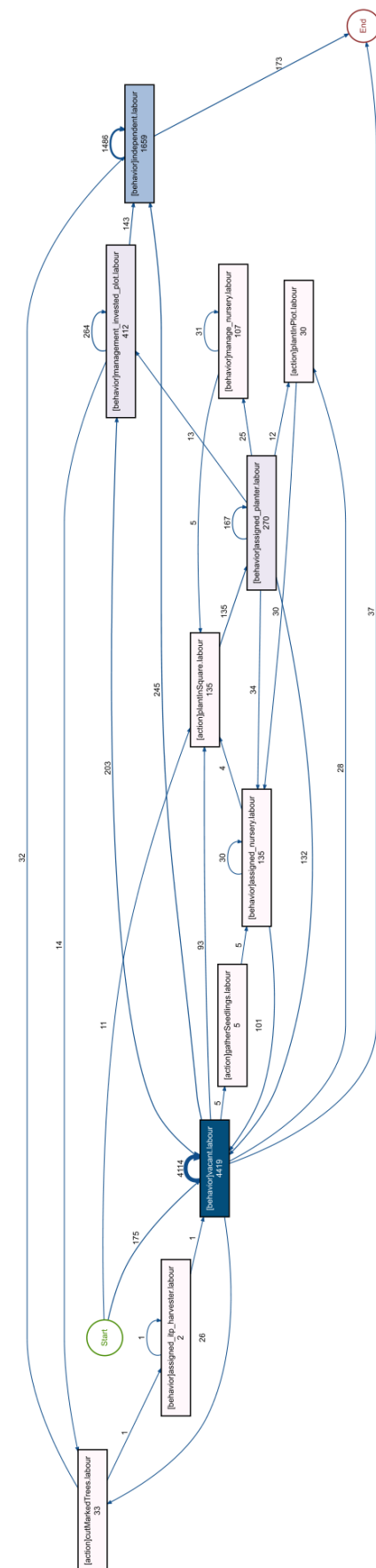


Figure D.16: Labour - PM

LUNTIAN Model Narratives

This appendix presents the three narrative outputs produced by ABM-VISTA for the LUNTIAN model.

E.1 Model Overview

Prompt: *You are a writing assistant. You will be given detailed descriptions of a complete simulation run of an agent-based model. Your task is to generate a clear, cohesive narrative summary that explains how the simulation model works that will cater to broad type of stakeholders. The summary should be written in prose form (not as bullet points), and it should focus on the dynamics of the model, including: (1) how agents behave and interact, (2) how the system evolves over time, (3) and what emergent patterns or outcomes are observed. Do not simply list events; instead, synthesize the information into a fluid, readable paragraph-style narrative that helps readers understand the mechanisms and evolution of the system during the simulation. Begin the narrative after reviewing the provided descriptions.*

Response: In the simulation model ‘LUNTIAN’, a complex ecosystem of interactions and processes unfolds among eleven distinct actors: market, special_police, comm_member, investor, plot, road, model, soil, trees, university, and labour. These actors, each with specific functionalities and behaviors, drive the dynamics of the model, creating a rich tapestry of emergent patterns and outcomes.

The simulation commences with the actor ‘model’ initiating fundamental environmental processes like adding precipitation and water flow, which are crucial for the growth and survival of trees. Simultaneously, ‘trees’ begin their lifecycle processes, such as calculating height and checking mortality, which are influenced by environmental factors and internal growth models. The trees’ growth and mortality rates, in turn, affect the soil and plot conditions, creating a feedback loop that shapes the ecosystem’s evolution.

The actor ‘labour’ plays a pivotal role as it interacts with nearly every other actor, executing tasks that range from planting and harvesting trees to managing nurseries and maintaining road sections. Labour’s actions are guided by economic incentives and environmental realities, such as calculating earnings, estimating tree values, and deciding on harvesting strategies. The ‘market’ actor assesses the economic viability of these operations by calculating total board feet, profits, and multipliers, providing the financial context for labour’s decisions.

The actor ‘special_police’ ensures the protection of plots and their neighborhoods, updating areas and guarding against potential threats. This policing activity

influences the ‘comm_member’ actors, who are responsible for marking trees, harvesting independently, and estimating values. Community members navigate the landscape, finding plots, updating their locations, and making decisions based on probabilistic harvesting models. Their actions feed into the overall ecosystem dynamics, affecting tree populations and plot conditions.

Investors, driven by potential active investments and risk assessments, engage in decisions that spur economic activities. They alert the ‘university’ about investment opportunities and potential profits, which, in turn, sends out laborers, harvesters, and planters. The university also replants plots, computes total costs, and monitors saplings, ensuring the balance between growth and harvest. This interplay between investors and the university drives economic activities while maintaining ecological sustainability.

Plots evolve through processes like reducing growth, computing coefficients, and updating details, which are influenced by environmental factors managed by the ‘model’ and ‘soil’ actors. The soil’s state affects tree growth, creating a dynamic where plot conditions and tree health are interconnected.

Emergent patterns in the simulation include the cyclic nature of tree growth and mortality, influenced by environmental factors and labour activities. Economic decisions made by the ‘market’ and ‘investor’ actors impact labour’s behavior, leading to fluctuations in harvesting and planting activities. The policing efforts of the “special_police” create a sense of security, influencing community members’ decisions and overall ecosystem stability.

The ‘trees’ actor experiences a lifecycle that includes growth, mortality, and recruitment, all of which are interlinked with the actions of labour and environmental processes. The roads and soil play critical roles in facilitating these processes, with road sections being removed when necessary and soil conditions influencing tree health.

Ultimately, the simulation model ‘LUNTIAN’ showcases a dynamic interplay between economic incentives, environmental realities, and human activities. The emergent patterns highlight the intricate balance between growth, harvesting, and sustainability, driven by the interactions of diverse actors in a simulated ecosystem.

E.2 Submodels

Prompt: *You are provided with detailed descriptions of a complete simulation execution for an agent-based model. Your task is to identify the different submodels and provide a narrative for each; do not list the processes. Below are the descriptions:*

Response: Each of these submodels plays a crucial role in the overall simulation, contributing to the accuracy and relevance of the model’s outputs. They work together to simulate a complex system that involves economic, environmental, and social factors, providing valuable insights into the dynamics of forest management

and sustainable development.

- *Market Dynamics Submodel.* This submodel focuses on the economic interactions and financial calculations relevant to the market actor. It involves processes like assessing the total board feet (BDFT) of lumber, determining profit margins, and calculating multipliers for financial decisions. The market actor plays a crucial role in evaluating the financial performance of harvesting and planting activities, which directly influences the decisions made by other actors, particularly investors and labourers.
- *Economic and Labour Interactions Submodel.* This submodel encompasses the interactions between the labour force and other economic actors. It includes tasks such as harvesting trees, replanting plots, and managing investments. The labour actor is central to this submodel, executing tasks that directly affect the economic outcomes and the physical state of the environment. This submodel also involves interactions with the university and market actors, ensuring that labour activities are aligned with economic goals and environmental sustainability.
- *Environmental Management Submodel.* This submodel deals with the management and monitoring of environmental factors, including the growth and mortality of trees, soil conditions, and water flow. Actors like the model, soil, and trees are integral to this submodel, performing tasks that simulate natural processes and environmental changes. This submodel ensures that the simulation accurately reflects the environmental impacts of various activities, such as deforestation and reforestation.
- *Investor and Risk Management Submodel.* This submodel focuses on the decision-making processes of investors, including evaluating risks, making investment decisions, and monitoring the performance of investments. The investor actor plays a key role in this submodel, interacting with the university and labour actors to ensure that investments are made in a way that maximizes returns while minimizing risks. This submodel also involves tasks related to updating risk levels and alerting stakeholders about investment opportunities.
- *Community and Harvesting Submodel.* This submodel involves tasks related to community members and their involvement in harvesting and management activities. The community member actor executes tasks such as marking trees for harvesting, finding plots, and computing earnings. This submodel also includes interactions with the labour and market actors, ensuring that community efforts are coordinated with broader economic and environmental goals. It plays a significant role in bridging between community-based activities and larger-scale management decisions.
- *Plot and Growth Monitoring Submodel.* This submodel focuses on the management and monitoring of specific plots of land, including updating plot details

and determining the growth of trees. The plot actor is central to this submodel, executing tasks that simulate the growth and recruitment of trees. This submodel ensures that the simulation accurately reflects the changes in the forest landscape over time, taking into account natural growth processes and human interventions.

- *Special Police and Security Submodel.* This submodel handles the security and monitoring of plots, ensuring that unauthorized activities are minimized. The special police actor is responsible for guarding plot neighborhoods, updating areas, and identifying open plots. This submodel interacts with the university actor, ensuring that security measures are aligned with broader management objectives.
- *Transportation Infrastructure Submodel.* This submodel deals with the management and maintenance of road infrastructure, which is crucial for accessing plots and transporting harvested materials. The road actor executes tasks related to the removal of road sections, which can impact the accessibility of certain areas. This submodel ensures that the transportation network is managed efficiently, facilitating the movement of labour and resources.
- *Simulation Initiation and Termination Submodel.* This submodel involves the initiation and termination of the simulation experiment. The model actor is responsible for tasks like adding precipitation, water flow, and terminating the experiment. This submodel ensures that the simulation process is initiated correctly and terminated appropriately, allowing for smooth execution and data collection.

E.3 Key Insights

Prompt: *You are provided with detailed descriptions of a complete simulation execution for an agent-based model. Your task is to identify and describe the critical and most important events in the simulation. Do not list the actors and its processes. Below are the descriptions:*

Response: Real-World Applications

- **Forest Management:** The model can help forest managers understand the complex interactions between different actors and their impact on forest ecosystems. This can aid in making informed decisions about harvesting, replanting, and sustainability.
- **Economic Analysis:** By simulating the financial processes involved in forestry, the model can provide insights into the economic viability of different management strategies.

- **Environmental Impact Assessment:** The model can help assess the environmental impact of different forestry practices, such as road construction and tree harvesting.
- **Policy Making:** Governments and policymakers can use the model to understand the effects of regulations on forestry management and to develop more effective policies.

Key Insights and Takeaways

- **Interaction Complexity:** The model highlights the intricate web of interactions between different actors in a forest ecosystem. Each actor's actions have far-reaching effects on other actors, emphasizing the need for holistic management strategies.
- **Dynamic Transitions:** The transitions between tasks are dynamic and probabilistic, reflecting the real-world uncertainty and variability in forestry management.
- **Environmental Influence:** Environmental factors, managed by actors like the model and soil, play a crucial role in the growth and harvesting of trees, highlighting the importance of ecological considerations in forest management.
- **Economic Viability:** The model provides insights into the economic aspects of forestry, helping to identify profitable and sustainable management practices.
- **Labor Management:** The role of labor is central to the model, underscoring the importance of workforce management in achieving forestry goals.
- **Untapped resources are important:** When trees die it can end quite potential labour and investor operations.

Complete Quantitative Evaluation of LUNTIAN Model Descriptions

This appendix presents the quantitative evaluation of the LUNTIAN model descriptions, along with the justifications for the scores.

Table F.1: Quantitative Evaluation of LUNTIAN ODD Description [5 = Excellent; 4 = Good; 3 = Adequate; 2 = Limited; 1 = Absent or Minimal]

Dimension	Sub-dimension	ODD Score	Justification
Structural Transparency	Agent definitions and attributes	5	Fully describes agent types, attributes, and roles.
	Environment setup	4	Provides detailed setup conditions and environment layout.
	Inter-agent interactions	3	Describes interaction rules but lacks depth on their sequence.
	State transitions and rules	3	Rules are stated, but process flows are not visualized.
	Parameter values and assumptions	5	Parameter values are listed clearly and consistently.
Behavioral and Dynamic Transparency	Temporal scheduling and decision sequencing	3	Specifies process ordering but not runtime dynamics.
	Emergent behavior	2	Does not describe how emergent behavior unfolds.
	Execution traceability	1	No provision for step-wise execution or logging.
Usability and Accessibility	Model purpose and rationale	5	Clearly states purpose and model rationale.
	Accessibility to non-modelers	2	Dense structure not aimed at lay users.
	Standardization and rigor	5	Uses a standard protocol followed in ABM literature.

Table F.2: Quantitative Evaluation of LUNTIAN ABM-VISTA Narrative [5 = Excellent; 4 = Good; 3 = Adequate; 2 = Limited; 1 = Absent or Minimal]

Dimension	Sub-dimension	ABM-VISTA Score	Justification
Structural Transparency	Agent definitions and attributes	4	Highlights agent logic through diagrams but lacks full formal description.
	Environment setup	3	Some initial context setup is inferred, but not exhaustively stated.
	Inter-agent interactions	5	Dynamic visualizations clearly illustrate agent interactions.
	State transitions and rules	5	Well-visualized flow of decision rules and changes over time.
	Parameter values and assumptions	2	Parameter values are not always exposed or explained.
Behavioral and Dynamic Transparency	Temporal scheduling and decision sequencing	5	Uses process diagrams to show time-sequenced decisions.
	Emergent behavior	5	Narrative output explicitly describes emergent outcomes.
	Execution traceability	5	Simulation logs trace decisions and actions step-by-step.
Usability and Accessibility	Model purpose and rationale	3	Partial articulation of model goals through outputs.
	Accessibility to non-modelers	5	Highly readable by non-experts using visual guides.
	Standardization and rigor	2	Not standardized; depends on implementation style.

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Abstract: Communicating simulation models to stakeholders remains a persistent challenge in agent-based modeling (ABM), particularly when models are intended to inform negotiation and decision-making. Participatory approaches such as co-design, visualization, and structured documentation have improved involvement, yet ABMs are still often perceived as “black boxes”, accessible mainly to developers. Existing practices focus heavily on the development phase, leaving post-development communication – where results must be interpreted and applied – weakly supported. Addressing this gap requires tools that translate complex model behaviors into accessible, meaningful forms for non-specialists, ensuring that ABMs can extend their impact beyond academic contexts and into practice.

This dissertation addresses the urgent yet underexplored question: *How can agent-based models be more effectively communicated to stakeholders during and after development?* It argues that ABM success in applied settings depends not only on model design and results, but also on accessibility – whether models can be understood, trusted, and reused by those they aim to serve. To meet this challenge, the work emphasizes post-development communication and offers both conceptual insights and practical tools.

The first contribution is a systematic scoping review of 65 academic publications, which categorizes communication tools and participation practices in ABM projects. The review identifies three critical gaps: (1) communication is concentrated during development, with little post-development support; (2) emergent behaviors – central to the explanatory power of ABMs – are rarely conveyed effectively; and (3) few studies systematically evaluate whether communication methods improve stakeholder understanding. The second contribution is the development of ABM-VISTA (Agent-Based Model – Visualization & Interpretation of Simulation Traces for Accessibility), a semi-automated framework that transforms raw simulation logs into interpretable visualizations and natural language narratives. The third is the design and implementation of LUNTIAN, an ABM simulating the governance dynamics of an industrial tree plantation in the Philippines. Developed in collaboration with local actors, LUNTIAN incorporates social agents (e.g., laborers, investors, university managers) and biophysical agents (e.g., trees, plots) interacting under varying regulatory and behavioral scenarios. It provides a concrete context for demonstrating the application and utility of ABM-VISTA. Finally, a case study applying ABM-VISTA to LUNTIAN illustrates how automated narrative generation and process mapping can support post-development communication. The results show that the tools provides clearer understanding of model structure, internal dynamics, and emergent outcomes. Preliminary usability tests and comparative assessments confirm that ABM-VISTA enhances model transparency and contributes to improved stakeholder comprehension.

Keywords: Agent-based Modeling, Forest Modeling, Communicating simulation models

Résumé: Communiquer des modèles de simulation aux différentes parties prenantes demeure un enjeu actuel dans la modélisation à base d’agents (ABM), notamment lorsque les modèles sont destinés à éclairer la négociation et la prise de décision. Les approches participatives telles que la co-conception, la visualisation et la documentation structurée permettent d’améliorer l’implication et la connaissance des différents stakeholders. Cependant, les ABM sont encore souvent perçus comme des « boîtes noires » accessibles principalement aux développeurs. Les pratiques existantes de support à la communication se concentrent principalement sur la phase de développement du modèle, délaissant toute communication post développement (moment où les résultats doivent être interprétés et appliqués). Combler cette lacune nécessite de développer des outils capables de traduire les comportements complexes des modèles dans une forme accessible et signification pour les non-spécialistes, garantissant ainsi que les ABM puissent avoir de l’impact au-delà des milieux académiques et ainsi être mis en pratique.

Cette thèse traite une problématique à la fois urgente et peu explorée : Comment les modèles à base d’agents peuvent-ils être communiqués plus efficacement aux parties prenantes pendant et après leur développement ? Elle montre que le succès des ABM, dans des contextes appliqués, dépend non seulement de la conception du modèle et de ses résultats, mais aussi de son accessibilité, c’est-à-dire de la possibilité pour les utilisateurs visés de comprendre, de faire confiance et de réutiliser le modèle. Pour relever ce défi, cette thèse met l’accent sur la communication post-développement et propose à la fois des éclairages conceptuels et des outils pratiques.

La première contribution de cette thèse est une revue de cadrage systématique de 65 publications académiques, qui catégorise les outils de communication et les pratiques participatives dans les projets de modélisation à base d’agents. La revue identifie trois lacunes critiques : (1) la communication se concentre sur la phase de développement, et peu sur les phases suivantes ; (2) les comportements émergents, pourtant centraux dans le pouvoir explicatif des ABM, sont rarement communiqués de manière efficace; et (3) peu d’études évaluent systématiquement si les méthodes de communication améliorent la compréhension des parties prenantes. La deuxième contribution est le développement d’ABM-VISTA (Agent-Based Model – Visualization & Interpretation of Simulation Traces for Accessibility), un cadre semi-automatisé qui transforme les traces brutes (logs) de simulations en visualisations interprétables et en récits en langage naturel. La troisième contribution est la conception et l’implémentation de LUNTIAN, un ABM simulant les dynamiques de gouvernance d’une forêt gérée suivant le modèle de plantation industrielle aux Philippines. Développé en collaboration avec des acteurs locaux, LUNTIAN intègre des agents sociaux (p. ex., ouvriers, investisseurs, gestionnaires) et des agents biophysiques (p. ex., arbres, parcelles) interagissant sous divers scénarios de gestion et de comportements des acteurs. Il fournit un contexte concret pour démontrer l’application et l’utilité d’ABM-VISTA. Enfin, une étude de cas appliquant ABM-VISTA à LUNTIAN illustre comment la génération automatique de récits et la cartographie des processus peuvent soutenir la communication post-développement. Les résultats montrent que l’outil offre une compréhension plus claire de la structure du modèle, de ses dynamiques internes et de ses résultats émergents. Des tests

préliminaires d'utilisabilité et des évaluations comparatives confirment qu'ABM-VISTA renforce la transparence du modèle et contribue à améliorer la compréhension des parties prenantes.

Mots-clés: Modélisation à base d'agents, Modélisation forestière, Communication des modèles de simulation
