Simulating Nudging Policies for Sustainable Urban Mobility

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ABSTRACT

With a focus on urban mobility, this paper explores how nudging mechanisms can promote sustainability in socio-technical systems, which capture the complex interplay among human, technological, and organizational components. While the optimization of technological aspects is typically addressed through normative policies, social dimensions often require softer strategies, such as nudging.

We propose a conceptual research agenda that builds on agent-based modeling (ABM) to investigate how nudging strategies can influence agents' behavior through utility perceptions and social awareness. The approach integrates value alignment principles to explicitly incorporate ethical and social justice considerations into the modeling process. The proposed model is intended to assess the impacts of behavioral change using urban sustainability indicators.

Expected contributions include conceptualizing value-aligned nudging mechanisms and developing an agent-based social simulation framework to examine their potential effects on sustainability-oriented behaviors in urban mobility systems, advancing multiagent systems (MAS) research for societal-impact policy design.

KEYWORDS

Nudging, Value alignment, Sustainable urban mobility, Socio-technical systems, Agent-based modeling

1 INTRODUCTION

Achieving sustainable development (SD) requires balancing social, environmental, and economic dimensions, commonly framed as the triple bottom line (TBL) approach [15]. Advancing this balance depends not only on technological and regulatory innovation but also on aligning individual and collective decision-making with emerging SD goals [5]. Such alignment requires individuals, businesses, and governments to incorporate sustainability principles into their practices and to systematically assess the impacts of their actions [5].

Behavioral change, however, remains one of the most challenging issues of sustainability transitions. Social and behavioral dynamics are often more effectively influenced by softer policy instruments, such as nudging, than by purely normative regulations [7, 30]. Yet, their integration into modeling and decision-support tools capable of predicting and assessing the outcomes of SD policies remains limited, particularly in urban mobility. Moreover, the explicit incorporation of value alignment frameworks and social justice principles into such tools is still underexplored.

This position paper outlines a conceptual and methodological research agenda for integrating nudging-based behavioral policies into agent-based modeling of sustainable urban mobility systems, with particular attention to value alignment and social justice considerations. This research is developed within the Alliance for Energy Transition (AET), a multidisciplinary consortium structured around six thematic axes, including energy efficiency and transition, sustainable mobility, and energy communities [10].

The remainder of this paper is organized as follows. The conceptual foundations and research gap are presented in section 2, while section 3 outlines the research agenda, including objectives, modeling perspective, methodology, and expected contributions. Opportunities and challenges are discussed in section 4, and section 5 concludes the paper.

2 CONCEPTUAL FOUNDATIONS AND RESEARCH GAP

Social structures can be represented as Socio-Technical Systems (STS), a framework that describes the complex interplay between human, technological, and organizational components in various contexts [3]. A perspective of STS's dimensions can be established based on the trichotomy of urban transportation, as discussed by Rossetti when exploring the "three main dimensions of urban transportation, namely Intelligent Transportation Systems (ITS), smart mobility, and sustainable communities, and how the three are interconnected" [21]. Analogously, the trichotomy of STS comprises intelligent, smart, and sustainable systems.

Intelligent systems prioritize system-wide optimal performance and rely on top-down normative regulation instruments, typically associated with critical and infrastructure-oriented applications. Smart systems, by contrast, center on individual utility and operate through market-based governance strategies, commonly associated with service-oriented and demand-driven contexts. Finally,

sustainable systems are driven by social awareness and prioritize resource preservation, typically emerging in participatory contexts characterized by collective engagement, social responsibility, and long-term resource stewardship.

Beyond defining these dimensions, their interrelationships are relevant to the proposed work, as they are not static, and transitions between them are possible. An intelligent system can evolve toward sustainability through the imposition of rules and regulations aimed at resource preservation; the shift from intelligent to smart systems is often mediated by market regulation dynamics; and a smart system may progress toward sustainability when agents of change – entities that, based on their individual utility, recognize the collective benefit of adopting sustainable behaviors – drive the transition. Finally, the intersection of all three dimensions gives rise to the concept of resource-level accessibility, which means resources must be available to all individuals and inherently implies considerations of equity, fairness, social justice, and inclusivity. A schematic illustration of such relationships and the intersection of STS's dimensions is depicted in Figure 1.

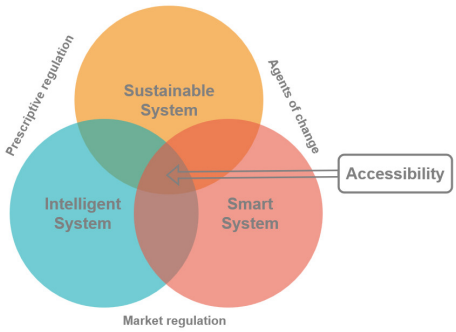

Figure 1: STS's dimensions: relationships and intersection.

Some aspects of an STS (particularly technological ones) can be optimized straightforwardly to improve its sustainability indicators. However, social aspects do not always respond well to more restrictive and normative optimization policies. For example, normative policies would be less effective in raising sustainability awareness and commitment, which becomes critical in socio-technical transitions from a smart to a sustainable system [12]. When it comes to behavioral aspects, it is possible to resort to strategies known as nudging to influence changes in individual behavior – and, therefore, in the behavior that emerges from the STS as a whole [7, 30].

Nudging, introduced by Thaler and Sunstein [26], refers to subtle interventions that steer individuals toward desirable behaviors without restricting their freedom of choice. These interventions leverage insights from behavioral economics and psychology to design environments that make preferred behaviors more intuitive or attractive. Recent studies have investigated the efficacy of nudging mechanisms (NM) across various domains, including sustainability objectives [1, 6, 9, 18, 23, 25, 31]. However, this perspective has been less explored in the realm of sustainable urban mobility.

When it comes to sustainability analysis, the Life Cycle Assessment (LCA) methodology stands out. A standardized framework originally developed to evaluate and quantify the environmental impacts of products, processes, or activities throughout their lifetimes [19, 32], it evolved into broader methodologies that approach sustainability's TBL model [15]. Nonetheless, such methods operate under static assumptions, ignore human behavioral dynamics [30], and struggle to incorporate uncertainty in human behavior [2]. That hinders their applicability to long-term sustainability transitions analysis and complex STS, where feedback loops emerge from dynamic human-environment interactions and behavior-driven changes are critical [16, 17]. Walzberg et al. [30] emphasize how these limitations impact the assessment of policies that focus on bounded rationality, which applies to nudging.

On the one hand, the literature shows that ABM approaches have been proposed to address this limitation in sustainability analysis, whether coupled with or not with LCA [4, 15]. On the other hand, an interesting gap exists in methodologies based on ABM and MAS for analyzing the effectiveness of sustainability policies that aim to influence behavioral change, particularly considering value alignment and urban mobility. Some publications highlight the significance of social norms and psychological factors in shaping commuting behavior [11, 20], and others suggest that integrating irrational and habit-driven decision models is essential for assessing individual behavior and broader systemic effects in sustainable mobility [22, 30, 31].

Therefore, there remains a lack of integrated methodological frameworks capable of systematically analyzing how nudging-based policies can influence sustainability in socio-technical urban mobility systems through ABM, while explicitly incorporating value alignment and social justice considerations. This paper advances a research agenda to address this gap by means of an agent-based conceptual and methodological framework to examine how behavioral policy instruments can steer emergent system dynamics toward more sustainable outcomes.

3 PROPOSED RESEARCH AGENDA

This section outlines the proposed research agenda, including its guiding questions, conceptual modeling perspective, and methodological approach toward using agent-based simulation to support behavioral policy design in socio-technical urban mobility systems.

3.1 Research Objectives and Conceptual Modeling Perspective

Since the social aspects of STS do not always respond effectively to purely normative optimization strategies, an alternative is to explicitly address bounded rationality and socially mediated decision-making. Based on that, this research addresses two questions.

(RQ_1) What soft control strategies can act as agents of change in making smart socio-technical systems more sustainable?

(RQ_2) What nudging mechanisms are most appropriate to steer the emerging behavior of multiagent systems to make them more sustainable?

Our hypothesis is that appropriately designed nudging mechanisms can shape agents' utility perceptions and social awareness, leading to emergent system behaviors more closely aligned with the collective good.

To address the research questions, this study pursues four main objectives:

(1) define NM to represent policies promoting sustainability by influencing populational behavioral changes;
(2) design an agent-based social simulation model to support the design of more sustainable STS and test the hypothesis;
(3) incorporate social dynamics into the STS by aligning the NM with human values through value alignment; and
(4) identify relevant urban sustainability indicators (USI) [14] to quantitatively assess the impact of populational behavioral change on STS's sustainability.

The choice of urban mobility for the application domain is particularly interesting, since its social aspects are closely related to the concepts of soft control, agents of change, and accessibility [21]. Additionally, it will be possible to leverage data (both real and synthetic) generated by the AET project in sustainable multimodal mobility to validate and evaluate the proposed model.

3.2 Methodological Approach

The conceptual, parametric framework for this research will be developed to represent the smart socio-technical system as a MAS, in which individual agents (e.g., individuals, households, organizations) interact within a defined environment, drawing on Sousa [8]. It should be generalizable across different urban mobility contexts, enabling the integration of various factors that affect the system's sustainability. Agents' decision-making will be guided by utility perceptions and social awareness, influenced by the nudging mechanisms implemented.

The incorporation of value alignment into the model, inspired by Holgado-Sánchez et al. [13], will be guided by key steps, such as defining relevant sustainability and social justice values and developing a contextual computational representation of these values. Additionally, modeling individual agents' value systems, so their particular preferences are reflected over collective values. Finally, investigating how NM can influence agents' perceived utility, causing their behavior to align with the collective values. The agents' decision-making processes may be further informed by behavioral theories, such as Triandis' Theory of Interpersonal Behavior [20], thereby allowing the inclusion of elements such as intention, affect, habit, and social factors in their choices.

The problem of influencing the STS towards sustainability will be formalized by drawing on Urbano [29], which should involve quantifying sustainability using relevant USI, formulating NM's impact on agent behavior, and operationalizing the concept of the collective good in terms of the chosen USI and social justice principles. The relevance criteria for USI selection will be guided by their alignment with the TBL approach. The simulations should be run under a baseline scenario without NM, and others that feature varied nudging interventions, enabling the collection of comprehensive data on agentic behavior and the overall system's sustainability performance.

In that sense, this study can rely on a Dynamic Synthetic Population of Porto [24], which consists of synthetically generated data that statistically reproduces distributions observed in real-world data while preserving privacy. Its dynamic nature allows the population to evolve over time by incorporating demographic changes, making it suitable for prospective scenario analysis and long-term sustainability assessments. Synthetic populations are widely used as inputs for agent-based simulations, including models of energy consumption and traffic pollution [27, 33]. Therefore, the baseline scenario for this study will be able to reproduce observed mobility patterns in Porto, Portugal's second-largest city, and the activity chains embedded in the synthetic population will provide the behavioral baseline from which KPIs can be derived, ensuring consistency with observed urban dynamics.

While this paper focuses on the conceptual and methodological foundations, subsequent work will involve developing detailed simulation models, empirical validation, and integration with sustainability assessment metrics to fully realize the proposed research agenda.

3.3 Expected Contributions to MAS for Societal Impact

The main contributions of the proposed work will be the conceptualization of an appropriate set of nudging mechanisms to make multiagent systems more sustainable, considering principles of social justice, and the development of an agent-based social simulation model incorporating value alignment. Since suitable USI will be selected to assess the system's sustainability, the resulting selection itself is also considered an additional contribution of this research.

More broadly, we aim to advance the analysis of the expected impacts of public policies focused on the social aspects of STS, contributing to the field of urban mobility. This aligns with the goals of the AET Agenda and the SDG 11 – Sustainable Cities and Communities, which focuses on creating inclusive, safe, and sustainable cities, addressing current pressing urbanization challenges [28].

Finally, this research can generate relevant social and technological impact, supporting actionable policy-making and potentially promoting the social good. For instance, a possible future development of the work could be its integration into ABM and LCA coupled models [2]. Although this is not its focus, such a possibility further enriches our proposal.

4 DISCUSSION: OPPORTUNITIES AND OPEN CHALLENGES

The proposed research agenda also raises some methodological and practical challenges that open promising avenues for future work. A central concern relates to model validation and verification, and data availability. Integrating methods for generating synthetic data and synthetic populations emerges as a key strategy to complement real-world datasets and enable the exploration of alternative scenarios, as discussed in the methodological framework.

Beyond data availability, the sensitivity of sustainability analyses to contextual specificities introduces a persistent trade-off between generalizability and contextual specificity. While the proposed hierarchical and parametric framework aims for generalizability across different contexts in urban mobility, focusing on a specific application domain might limit the direct transferability of nudging strategies and simulation results to other sustainability challenges.

The proposed agent-based nudging framework, while grounded in sustainable urban mobility, may also extend to other forms of urban movement shaped by bounded rationality and socially mediated decision-making, such as tourist mobility, where route choices

are influenced not only by efficiency but also by experiential, social, and contextual factors [34]. As part of the same socio-technical system as daily commuting, tourist routing decisions contribute to congestion, environmental pressure, and spatial inequalities, particularly in cities affected by overtourism, making this domain suitable for exploring soft-control interventions. Although tourism contexts lie beyond the scope of this study, this possible extension highlights a promising direction for future research integrating agent-based nudging frameworks with tourist route planning and management systems.

Finally, the design and deployment of behavior-influencing mechanisms raise important ethical and societal considerations. Ensuring transparency, fairness, and alignment with sustainability values will be essential to preventing unintended consequences and supporting responsible policy design. Addressing these challenges can advance multiagent methodologies that inform decision-support tools and policy strategies for more sustainable and equitable urban mobility systems.

5 CONCLUSION

This paper addressed a persistent gap in sustainability analysis: the limitations associated with assessing behavior-oriented policies in socio-technical systems. Our research agenda proposes a framework based on agent-based modeling to investigate the effectiveness of nudging mechanisms in fostering sustainability awareness and promoting more sustainable outcomes within smart socio-technical systems, particularly in urban mobility.

This study aims to conceptualize a structured set of nudging strategies that can influence agents toward behaviors that prioritize the collective good, with special attention to integrating value alignment and social justice principles. Our hypothesis is that strategically inserting such mechanisms can steer the emergent behavior of a multiagent system toward more sustainable performance by shaping agents' interpretation of utility and social awareness. The main expected contributions of this research are the operationalization of value-aligned nudging mechanisms and the development of an agent-based social simulation framework to test their effects on sustainability-oriented behaviors within socio-technical urban mobility systems.

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REFERENCES

[1] Marius Alt, Hendrik Bruns, Nives DellaValle, and Ingrida Murauskaite-Bull. 2024. Synergies of interventions to promote pro-environmental behaviors – A meta-analysis of experimental studies. *Global Environmental Change* 84 (Jan. 2024), 102776.

[2] Paul Baustert and Enrico Benetto. 2017. Uncertainty analysis in agent-based modelling and consequential life cycle assessment coupled models: A critical review. *Journal of Cleaner Production* 156 (July 2017), 378–394.

[3] Gordon Baxter and Ian Sommerville. 2011. Socio-technical systems: From design methods to systems engineering. *Interacting with Computers* 23, 1 (2011), 4–17.

[4] Thomas Beaussier, Sylvain Caurla, Véronique Bellon-Maurel, and Eleonore Loiseau. 2019. Coupling economic models and environmental assessment methods to support regional policies: A critical review. *Journal of Cleaner Production* 216 (April 2019), 408–421.

[5] David Boix-Cots, Francesc Pardo-Bosch, Ana Blanco, Antonio Aguado, and Pablo Pujadas. 2022. A systematic review on MIVES: A sustainability-oriented multi-criteria decision-making method. *Building and Environment* 223 (Sept. 2022).

[6] Andrea Ceschi, Riccardo Sartori, Stephan Dickert, Andrea Scalco, Elena M. Tur, Francesco Tommasi, and Keren Delfini. 2021. Testing a norm-based policy for waste management: An agent-based modeling simulation on nudging recycling behavior. *Journal of Environmental Management* 294 (Sept. 2021), 112938.

[7] Mark Coeckelbergh. 2021. AI for climate: freedom, justice, and other ethical and political challenges. *AI and Ethics* 1, 1 (Feb. 2021), 67–72.

[8] João Bernardo Narciso de Sousa. 2021. *Carbon Market Multi-Agent Simulation Metamodel: a Testbed for Coordination Mechanisms in Sociotechnical Systems.* Masters Thesis. Faculty of Engineering, University of Porto, Porto, Portugal.

[9] Bianca Maria Deconcini. 2024. Personal Values and Community-Centric Environmental Recommender Systems: Enhancing Sustainability Through User Engagement. In *Proceedings of the 18th ACM Conference on Recommender Systems* (Bari, Italy) *(RecSys '24)*. Association for Computing Machinery, New York, NY, USA, 1342–1347.

[10] Efacec. 2023. ATE (Alliance for Energy Transition) signs terms of acceptance of the Recovery and Resilience Pact agenda. https://www.efacec.com/news/ate-alliance-for-energy-transition-signs-terms-of-acceptance-of-the-recovery-and-resilience-pact-agenda/ Last accessed 2026-02-18.

[11] Robert Greener, Daniel Lewis, Jon Reades, Simon Miles, and Steven Cummins. 2022. Incorporating social norms into a configurable agent-based model of the decision to perform commuting behaviour.

[12] Paula Hansen, Xin Liu, and Gregory M. Morrison. 2019. Agent-based modelling and socio-technical energy transitions: A systematic literature review. *Energy Research & Social Science* 49 (March 2019).

[13] Andrés Holgado-Sánchez, Javier Bajo, Holger Billhardt, Sascha Ossowski, and Joaquín Arias. 2025. Value Learning for Value-Aligned Route Choice Modeling via Inverse Reinforcement Learning. In *Value Engineering in Artificial Intelligence*, Nardine Osman and Luc Steels (Eds.), Vol. 15356. Springer Nature Switzerland, Cham, 40–60.

[14] Lu Huang, Jianguo Wu, and Lijiao Yan. 2015. Defining and measuring urban sustainability: a review of indicators. *Landscape Ecology* 30, 7 (Aug. 2015), 1175–1193.

[15] Kamran Khan and Thomas Henschel. 2024. LCT-Based Framework for the Assessment of Sustainability: From the Perspective of Literature Review. *Social Indicators Research* 175, 3 (Dec. 2024), 1–20.

[16] Kai Lan and Yuan Yao. 2019. Integrating Life Cycle Assessment and Agent-Based Modeling: A Dynamic Modeling Framework for Sustainable Agricultural Systems. *Journal of Cleaner Production* 238 (Nov. 2019), 117853.

[17] Alice Micolier, Philippe Loubet, Franck Taillandier, and Guido Sonnemann. 2019. To what extent can agent-based modelling enhance a life cycle assessment? Answers based on a literature review. *Journal of Cleaner Production* 239 (Dec. 2019), 118123.

[18] Oriana Mosca, Andrea Manunza, Sara Manca, Giuliano Vivanet, and Ferdinando Fornara. 2024. Digital technologies for behavioral change in sustainability domains: a systematic mapping review. *Frontiers in Psychology* 14 (Jan. 2024).

[19] Evanthia A. Nanaki. 2021. Chapter 5 - Climate change mitigation and electric vehicles. In *Electric Vehicles for Smart Cities*, Evanthia A. Nanaki (Ed.). Elsevier, 141–180.

[20] Khoa Nguyen and René Schumann. 2021. An Exploratory Comparison of Behavioural Determinants in Mobility Modal Choices. In *Advances in Social Simulation*, Petra Ahrweiler and Martin Neumann (Eds.). Springer International Publishing, Cham, 569–581.

[21] Rosaldo José Fernandes Rossetti and Faculty of Engineering, University of Porto. 2022. [Aggregation Exams] / Rosaldo José Fernandes Rossetti.

[22] Chinmaya Samal, Abhishek Dubey, and Lillian Ratliff. 2019. Mobilytics-Gym: A Simulation Framework for Analyzing Urban Mobility Decision Strategies. In *2019 IEEE International Conference on Smart Computing (SMARTCOMP)*. 283–291.

[23] Marta Santos Silva. 2022. Nudging and Other Behaviourally Based Policies as Enablers for Environmental Sustainability. *Laws* 11, 1 (Feb. 2022), 9.

[24] Iohan Sardinha, Mariam Afonso, Jadna Cruz, Rosaldo Rossetti, and Ana Paula Rocha. 2025. Towards Dynamic Population Synthesis Through the Use of Machine Learning. In *Advances in Social Simulation*, Marcin Czupryna, Bogumił Kamiński, and Harko Verhagen (Eds.). Springer Nature Switzerland, Cham, 439–449.

[25] Sarah Shtaierman, Catarina Fontes, and Christoph Lütge. 2025. The Potentials and Limitations of Agent-Based Models for Urban Digital Twins: Insights From a Surveillance and Behavioral Nudging Simulation. *Urban Planning* 10, 0 (Jan. 2025).

[26] Richard H. Thaler and Cass R. Sunstein. 2008. *Nudge: Improving Decisions about Health, Wealth, and Happiness.* Yale University Press.

[27] Michele Tirico, Valentin Le Bescond, Delphine Sengelin, Pascal Gastineau, and Arnaud Can. 2025. Multi-scale comparison of modeling chains for traffic-related air pollutant emission assessment. *Sustainable Cities and Society* 129 (2025), 106354.

[28] United Nations. 2025. Cities: United Nations Sustainable Development. https://www.un.org/sustainabledevelopment/cities Last accessed 2026-02-18.

[29] Maria Joana Malaquias Pires Urbano. 2013. *A situation-aware and social computational trust model.* Ph.D. Dissertation. University of Porto (Portugal).
[30] Julien Walzberg, Thomas Dandres, Nicolas Merveille, Mohamed Cheriet, and Réjean Samson. 2019. Assessing behavioural change with agent-based life cycle assessment: Application to smart homes. *Renewable and Sustainable Energy Reviews* 111 (Sept. 2019), 365–376.
[31] Shiqing Wu, Quan Bai, and Sotsay Sengvong. 2018. GreenCommute: An Influence-Aware Persuasive Recommendation Approach for Public-Friendly Commute Options. *Journal of Systems Science and Systems Engineering* 27, 2 (April 2018), 250–264.
[32] Lúcia Helena Xavier, Marianna Ottoni, and Leonardo Picanço Peixoto Abreu. 2023. A comprehensive review of urban mining and the value recovery from e-waste materials. *Resources, Conservation and Recycling* 190 (2023), 106840.
[33] Yohei Yamaguchi, Yuto Shoda, Shinya Yoshizawa, Tatsuya Imai, Usama Perwez, Yoshiyuki Shimoda, and Yasuhiro Hayashi. 2023. Feasibility assessment of net zero-energy transformation of building stock using integrated synthetic population, building stock, and power distribution network framework. *Applied Energy* 333 (March 2023), 120568.
[34] Piotr Zientara, Magdalena Jażdżewska-Gutta, Monika Bąk, and Anna Zamojska. 2024. What drives tourists' sustainable mobility at city destinations? Insights from ten European capital cities. *Journal of Destination Marketing & Management* 33 (2024), 100931.