March 17th — 18th, 2021 | Darmstadt, Germany
Interdisciplinary Conference on Production, Logistics and Traffic
www.icplt.org

A micro-macro modelling approach for evaluating railway infrastructure projects

Joana Cunha[1], Vasco Reis[1] and Paulo Teixeira[1]

[1] *CERIS, CESUR, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal*

Abstract. Railway infrastructure managers must plan investments taking into account both the infrastructure's medium- and short-term capacity and maintenance needs, as well as the long-term strategic development goals. However, available methodologies for long-term modelling fail to address the dynamic response of the demand to the varying levels of service, and the changes in stakeholder interactions, which will naturally result from significant capacity and technology changes in the network. Conversely, while micro-simulation can capture the actors' individual behaviours, a model encompassing the full transportation system would be computationally demanding. Aiming to provide decision-makers with a tool to better assess the potential success and long-term implications of infrastructure projects, the present work develops a novel modelling framework that connects two distinct modules: the macro module simulates a freight transportation market, describing the behaviours and interactions between the main stakeholders; and the micro module reproduces the daily transport operations under the conditions set by macro module agents. These modules continuously communicate with each other, updating critical information that affects the agents' decision-making behaviour. This approach enables monitoring the short-term consequences of infrastructure and service changes on operational performance, and simultaneously capturing the long-term evolutions in the freight transportation system, while lessening computational demands.

1 Introduction

Railway infrastructure planning aims to prepare the current and future infrastructure's developments to handle the perceived evolutions of the transportation system over long periods of time. This planning must balance, on the one hand, the infrastructure's maintenance and renovation needs, the current and future demands, and, on the other, the Government's strategic development goals, as well as the foreseen infrastructure developments in other countries.

Cost-Benefit Analysis, generally employed for planning infrastructure projects, is unable to capture the dynamic response of the demand to variations in service provision, resulting from technological and capacity changes in the infrastructure. Furthermore, approaches for long-term modelling, such as System Dynamics, disregard the long-term impacts of such innovations on the interactions amongst market stakeholders, as they assume a static relationship between them [1], [2].

The freight transport and infrastructure planning literatures recognize the existence of two main levels of analysis: the macro-level, comprised of the strategic decisions of stakeholders, such as Policy-makers; and the micro-level, reflecting the tactical-operational decisions of operators, and their impact on service provision. However, very few works attempt to consider both levels when modelling the freight transportation system. Existing approaches to combine long-term modelling and micro-simulation, such as [2], [3], generally employ System Dynamics for the long-term analysis, and only consider one-way communications between levels, forgoing the ensuing responses.

The complex nature of the freight transportation system calls for a technique able to capture the behaviours and interactions of agents at both levels of analysis, as well as the influence of each level on its counterpart. Changes in stakeholder behaviour cannot be captured by static assumptions, thus we argue that Agent-Based Modelling would be more suitable to capture both the immediate, and the long-term reactions of system actors. Nevertheless, a micro-simulation encompassing the full system would be unfeasible, as such a model would have extremely high computational demands: a combined approach is needed to solve this conundrum.

This work aims to address these issues by developing a novel modelling framework that enables a bidirectional communication between these two levels over the planning period. Such an approach should aid infrastructure managers better assess the effects of infrastructure projects.

2 Modelling complex large-scale systems

Three modelling approaches are found in literature that offer strategies to capture complex large-scale systems, while simultaneously lessening computational demands and simulation times.

Hybrid Modelling aims to capture the feedback cycles between different spatial, and temporal, scales of the system through the combination of different methods: typically using continuous approaches for long-term evolutions, and discrete methods for short-term interactions [4]. Its uses range from modelling ecological environments [5] to market competition [6]–[8], transportation [9], and urban sprawl [10] analyses.

Multi-level Agent-based Modelling acknowledges that complex systems have multiple levels of aggregation, and that the entities in these levels often have an inherent hierarchy. This approach employs aggregation-disaggregation techniques to capture both long- and short-term behaviours, and detect emergent phenomena and spatial structures [11], [12]. Examples of this approach are rather limited to flow [13] and crowd behaviour [14] simulation, and the modelling of biological and ecological systems. The greatest drawback of this technique lies in the loss of agents' individual characteristics during the aggregation process [12], [15].

The Distributed Systems (or High-Level Architecture) approach focuses on separating a complex system's components into sub-models (called federates), which are run independently, sometimes on different computers, and integrated by an interface that ensures both time coordination and information exchange. This modular structure allows combining different methods, as each federate is built separately, and reusing models for different case studies, by adjusting only the relevant federates [16]. Despite the complexity of its implementation, some applications are found in supply chain modelling [17]–[19].

3 Freight transport market model

Inspired by previous methodologies, we propose a novel model design that connects two sub-models: the macro module reproduces the (long-term) strategic decision-making of the major stakeholders, using Agent-Based Modelling; and the micro module simulates the day-to-day logistic operations under the resulting market conditions, blending Agent-Based Modelling and Discrete Event Simulation. During the simulation period, these modules interact with one another, relaying critical information between agent counterparts, which influences their actions. In order to reduce computational demand, the highly detailed micro module is periodically run for a brief period (a "representative" week), and its results returned to the macro module; this allows monitoring relevant short-term developments, without needlessly overloading the simulation. Figure 1 illustrates the proposed model architecture.

In the macro module, the freight transport Demand is represented as an aggregated evolution of cargo being transported between locations over the planning period. The global evolution of the Demand should be responsive to external drivers, such as fluctuations in GDP, and eventual regional disparities, which translate into changes in the OD matrix. During the simulation, the macro module estimates the evolution of the OD matrix for the next period, and that of the shippers' preferences and perception regarding the provided transportation services. This information is conveyed to the micro module, where the Demand behaviour is manifested by two separate entities: TEUs materialize the cargo shipments, and are created based on the expected OD matrix; and Forwarders are responsible planning their transport, grounding their modal choice on the communicated utility function. The micro module returns the generated OD matrix, as well as the updated service satisfaction levels to the macro module, prompting it to re-evaluate long-term trends.

Transport operators are represented in the macro module by two agent types: Road Operators, and Rail Operators. These agents aim to capture the Demand and consolidate their market positions, adopting diverse strategies to achieve this: either by direct price competition, or by offering new services; they may even opt to cooperate with one another and create intermodal services. Besides service provision, these agents must manage their respective vehicle fleets, and may invest in new technologies; here, Rail Operators are conditioned by the technical features of the railway infrastructure. Information regarding the offered services and the fleets' characteristics is sent to the micro module, where the Truck and Train agents perform the transportation of shipments assigned by the Forwarder. The micro model then reports the ensuing performance measures, prompting the transport operators to reassess their strategy.

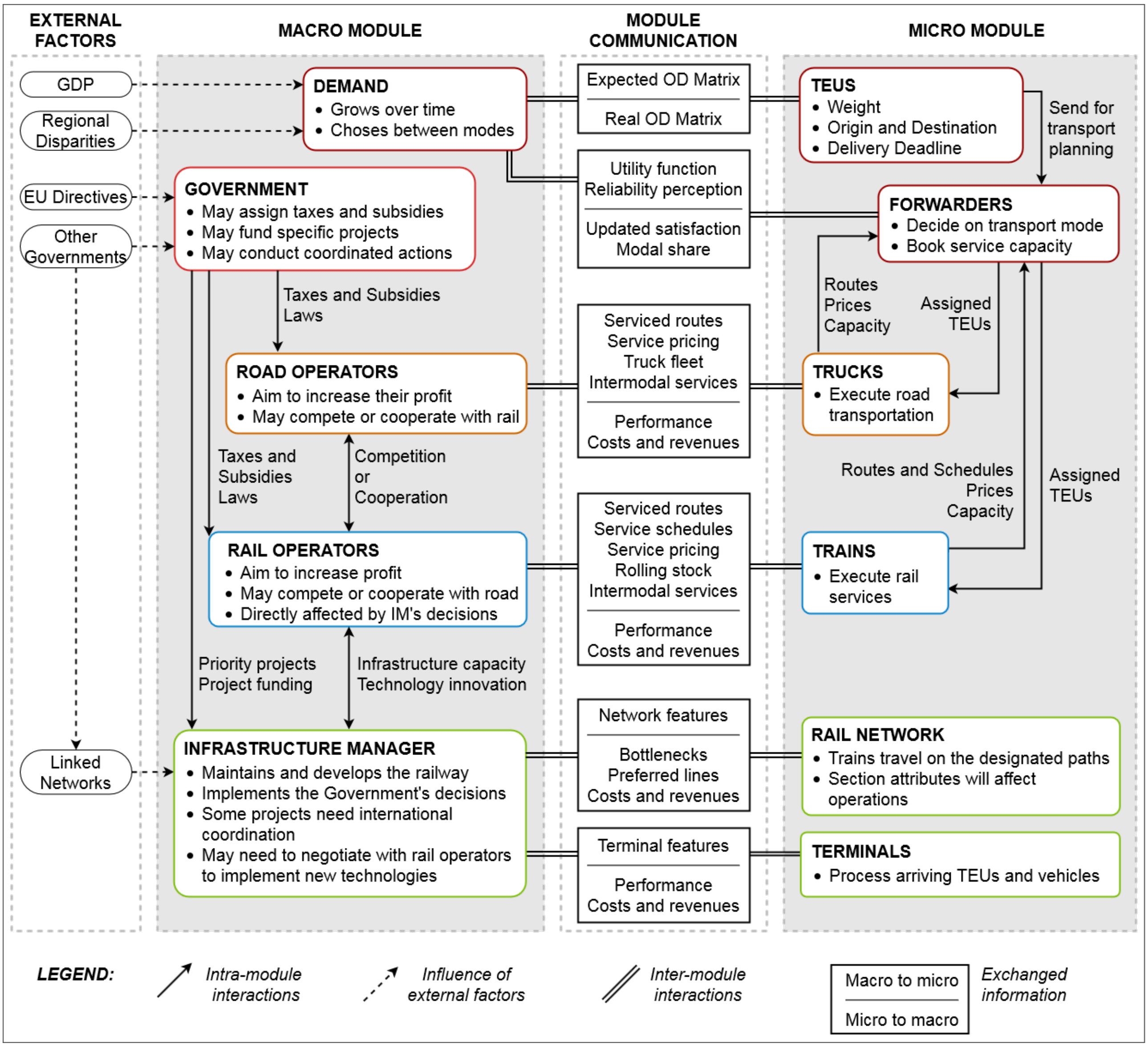

Figure 1. Micro-macro model concept for capturing both short- and long-term system responses to infrastructure projects.

Parallel to the previous agents' actions, the Government establishes a set of policies to regulate and guide the system towards the defined national strategic goals. These goals are influenced by EU Directives (e.g., the reduction of GHG emissions), or part of coordinated actions with neighbouring countries to invest on complementary infrastructure. Based on these ambitions, the Government may apply penalties or incentives to transport operators (affecting their operational costs) and alter regulations on their practices, or signal priority infrastructure projects to the Infrastructure Manager.

The final element in the macro module is the Infrastructure Manager, responsible for planning the railway infrastructure over several decades. In this work, the user of the model is intended to act as the Infrastructure Manager. Detailed information is provided regarding the current infrastructure, encompassing the rail lines and the terminals, each with their specific attributes (such as typology, capacity, and used equipment). The user also has access to a portfolio of proposed projects and their features: implementation cost and time; impact on transport operations; if they are priority, or mandatory, interventions; applicable precedence rules; and applicable mutual exclusion rules between projects. Some investments may be complemented by negotiations with Rail Operators, to ensure they cooperate with the intended changes. The user's decisions are implemented in the micro module by changing the railway and terminals' features accordingly, which will affect transport operations. The micro module should then reveal important information on how the transport operators use the network, how they may adapt to the new conditions, and where bottlenecks might be located.

4 Conclusion

This work develops a novel modelling framework for simulating freight transportation systems that simultaneously captures the long-term aspect of stakeholders' strategic decision-making, and the short-term implications of their decisions on operational performance. Applied to the problem of infrastructure planning, this framework should allow Infrastructure Managers to gain a greater awareness of the potential responses of system agents, and eventual unforeseen ramifications of infrastructure interventions.

The main contribution of the proposed approach lies in the replication of these two facets of the system on distinct modules that continuously communicate with each other. This allows both coordinating the different temporal scales of each module's developments, and lessening the computational demands of the full model.

The modular nature of this model further enables testing several variants of each module's internal structure without compromising the overall model's integrity. As such, it can be tailored to different markets - with one or several operators for each mode, or different interaction rules -, or different case studies. Moreover, numerous decision-making logics and behaviour mechanics may be tried for each agent; thus, broadening the scope of potential responses to infrastructure changes.

Further developments include applying the micro-macro model to the Atlantic Corridor of the TEN-T network, and testing some investment scenarios, such as the introduction of the Modalohr technology.

Acknowledgements

This research work was funded by the Fundação para a Ciência e Tecnologia (FCT – Portugal), through grant PD/BD/142950/2018.

References

1. R. D. Collins, R. de Neufville, J. Claro, T. Oliveira, A. P. Pacheco: Forest fire management to avoid unintended consequences: A case study of Portugal using system dynamics. J. Environ. Manage., **130**, pp. 1–9, (2013).
2. T. Nguyen, S. Cook, V. Ireland, I. Gunawan: A hybrid approach to Cost-Benefit Analysis in transport infrastructure projects. *Proceedings of the International Conference on System Science and Engineering (ICSSE)*, pp. 569–574, (2017).
3. G. de Jong, H. Gunn, W. Walker: National and international freight transport models: An overview and ideas for future development. Transp. Rev., **24** (1), pp. 103–124, (2004).
4. A. Stéphanou, V. Volpert: Hybrid Modelling in Biology: A Classification Review. Math. Model. Nat. Phenom., **11** (1), pp. 37–48, (2016).
5. G. Wallentin, C. Neuwirth: Dynamic hybrid modelling: Switching between AB and SD designs of a predator-prey model. Ecol. Modell., **345**, pp. 165–175, (2017).
6. J. Foster, J. Potts: A micro-meso-macro perspective on the methodology of evolutionary economics: Integrating history, simulation and econometrics. In: U. Cantner et al. (eds.): *Schumpeterian Perspectives on Innovation, Competition and Growth*, Heidelberg: Springer, pp. 55–70, (2009).
7. N. Strachan, R. Kannan: Hybrid modelling of long-term carbon reduction scenarios for the UK. Energy Econ., **30** (6), pp. 2947–2963, (2008).
8. A. J. Heppenstall, M. H. Birkin, A. J. Evans: A hybrid multi-agent/spatial interaction model system for petrol price setting. Trans. GIS, **9** (1), pp. 35–51, (2005).
9. R. Tu, I. Kamel, A. Wang, B. Abdulhai, M. Hatzopoulou: Development of a hybrid modelling approach for the generation of an urban on-road transportation emission inventory. Transp. Res. Part D Transp. Environ., **62**, pp. 604–618, (2018).
10. S. Saeedi: Integrating macro and micro scale approaches in the agent-based modeling of residential dynamics. Int. J. Appl. Earth Obs. Geoinf., **68**, pp. 214–229, (2018).
11. G. Morvan: Multi-level agent-based modeling - A literature survey. CoRR, pp. 1–27, (2013).
12. P. Mathieu, G. Morvan, S. Picault: Multi-level agent-based simulations: Four design patterns. Simul. Model. Pract. Theory, **83**, pp. 51–64, (2018).
13. N. T. Ngoc Anh, J.-D. Zucker, N. Huu Du, A. Drogoul, D.-A. Vo: A hybrid macro-micro pedestrians evacuation model to speed up simulation in road networks. In: F. Dechesne et al. (Eds.): *Advanced Agent Technology. AAMAS 2011. Lecture Notes in Computer Science, vol. 7068*, Heidelberg: Springer, pp. 371–383, (2012).
14. L. Navarro, F. Flacher, V. Corruble: Dynamic Level of Detail for Large Scale Agent-Based Urban Simulations. *10th International Conference on Autonomous Agents and Multiagent Systems (AAMAS'11)*, pp. 701–708, (2011).
15. D.-A. Vo, A. Drogoul, J.-D. Zucker: Multi-Level Agent-Based Modeling: a Generic Approach and an Implementation. In: D. Barbucha et al. (Eds.): *Advanced Methods and Technologies for Agent and Multi-Agent Systems*, Amsterdam: IOS Press, pp. 91–101, (2013).
16. A. Anagnostou, S. J. E. Taylor: A distributed simulation methodological framework for OR/MS applications. Simul. Model. Pract. Theory, **70**, pp. 101–119, (2017).
17. A. G. Bruzzone, R. Mosca, R. Revetria, E. Bocca, E. Briano: Agent Directed HLA Simulation for Complex Supply Chain

Modeling. Simulation, **81** (9), pp. 647–655, (2005).

18. S. Jain, F. Riddick, A. Craens, D. Kibira: Distributed simulation for interoperability testing along the supply chain. *Proceedings of the 2007 Winter Simulation Conference*, pp. 1044–1052, (2007).
19. K. Katsaliaki, N. Mustafee, S. J. E. Taylor, S. Brailsford: Comparing conventional and distributed approaches to simulation in a complex supply-chain health system. J. Oper. Res. Soc., **60** (1), pp. 43–51, (2009).